

**COMPUTER SIMULATION
OF
HIGHWAY TRAFFIC**

**A Thesis submitted in the
Faculty of Applied Science, University of Newcastle upon Tyne,
for the degree of Doctor of Philosophy.**

NEWCASTLE UNIVERSITY LIBRARY

087 12042 4

Thesis U171

STEWART SUMNER BSc.

April, 1970

SUMMARY

The work is concerned with the simulation of highway traffic using a high speed electronic digital computer, and is divided into four parts.

The first chapter opens by describing simulation techniques in general, and traffic simulation by digital computer in particular. The advantages and disadvantages of the method are discussed. Early work in the U.S.A. and the U.K. is described, and then comparisons are drawn between the major current fields of study.

The second chapter describes the formulation of a model to simulate traffic behaviour at a traffic signal controlled intersection. The object of the simulation is to determine an accurate description of the decrease in capacity of the intersection with an increase in the volume of right turning traffic. The results of the simulation are presented and analysed. Recommendations are made for incorporation into current traffic engineering practice.

The third chapter describes the formulation of a model to simulate traffic moving along a long two-lane weaving section. Car following theory is used to describe the motion of the vehicles, and a model of the lane-change decision proposed and discussed. The effect of changes in the physical characteristics and traffic characteristics on the delay to vehicles using the section are predicted.

The final chapter is concerned with the photographic equipment used to collect and analyse the field data necessary for the construction of accurate models.

ACKNOWLEDGEMENTS

I should like to thank the following people for help and advice in various aspects of the preparation of this work..

Dr. J. Baty

Professor W.F. Cassie

Professor T. Constantine

Miss E.M. Davies

Mr. A.C. Dick

Mr. M.E.H. Larcombe

Mr. J. Robinson

Mrs. F. Smyth

Professor T.E.H. Williams

Mr. A.P. Young

Stewart L. Sumner

April, 1970

CONTENTS

REFERENCES : References are typed on the blue paper bound at the end of each chapter.

	<u>Page</u>
CHAPTER 1 : SIMULATION	1
1.1 METHODS OF SIMULATION	2
1.1.1 Physical Models	2
1.1.2 Analogue Models	2
1.1.3 Mathematical Models	4
1.1.4 Digital Models	5
1.2 TRAFFIC SIMULATION BY DIGITAL COMPUTER	7
1.2.1 Traffic Analysis	8
1.2.2 KDF9 and Algol 60	10
1.2.3 The Monte Carlo Technique	15
1.2.4 Random Number Generation	16
1.2.5 Field Data	18
1.2.6 Testing the Model	19
1.2.7 Simulation Studies	19
1.3 SOME SIMULATION MODELS	20
1.3.1 Early work in the United States	20
1.3.2 Early work at the Road Research Laboratory	24
1.3.3 On-ramp models	26
1.3.4 Single Traffic Signal Controlled Intersections	32
1.3.5 Linked traffic Signals and Networks	37
1.3.6 Open Road Models	44
1.4 CONCLUSIONS	47

	<u>Page</u>
CHAPTER 2 : TRAFFIC SIGNAL-SIMULATION	48
2.1 THE PROBLEM	
2.1.1 The Right Turn Manoeuvre	48
2.1.2 Road Research Laboratory Recommendations	48
2.1.3 Other Work on the Right-Turning Problem	52
2.1.4 A Solution	57
2.2 DATA COLLECTION AND ANALYSIS	58
2.2.1 The Test Site	58
2.2.2 Gap Acceptance	59
2.2.2.1 Collection of gap acceptance data	60
2.2.2.2 Gaps and Lags	62
2.2.2.3 Analysis of Photographic data	63
2.2.2.4 Analysis Methods	65
2.2.2.5 Analysis and Conclusions	75
2.2.3 Arrival Distributions	77
2.3 THE TRAFFIC MODEL	82
2.3.1 In General	82
2.3.2 Vehicle Arrivals and Queueing	82
2.3.3 Signals	84
2.3.4 Queue Clearance and Saturation Flows	85
2.3.5 Saturation Flow of Right Turning Vehicles	86
2.3.6 Delays	90
2.4 THE PROGRAM	91
2.4.1 In General	91
2.4.2 Identifiers	91
2.4.3 Procedures	98
2.4.4 Text of Program	98
2.4.5 Input	99
2.4.6 Output	99
2.4.7 Size	103
2.4.8 Running Times	103

	<u>Page</u>
2.5 PROGRAM TESTING	104
2.5.1 Mechanical Tests	104
2.5.2 Calibration Tests	106
2.5.3 Simulation Times and Random Numbers	108
2.6 PRODUCTION RUNS	109
2.7 RESULTS	111
2.7.1 Right Turning Vehicle Factor	111
2.7.2 Saturation Flows and Degrees of Saturation	115
2.7.3 Delay	116
2.7.4 Comparison with Other Work	118
2.7.5 Application of Results and Conclusions	120
CHAPTER 3 : WEAVING SECTION SIMULATION	123
3.1 DELAY ON WEAVING SECTIONS	123
3.2 CAR FOLLOWING THEORY	126
3.2.1 Constant Sensitivity	126
3.2.2 Step Function	127
3.2.3 Reciprocal Spacing	128
3.2.4 Visual Angle Models	128
3.2.5 The Model Adopted	129
3.2.6 Restrictions	129
3.3 WEAVING	131
3.4 THE MODEL	133
3.4.1 Scanning Technique	133
3.4.2 Congestion	134
3.4.3 Updating	134
3.4.4 Vehicle Generation	135
3.4.5 Queue Clearance	137
3.4.6 Weaving Vehicles	143
3.4.7 Acceleration Calculations	143
3.4.8 Output	144

	<u>Page</u>
3.5 THE PROGRAM	146
3.5.1 Egdon Algol	146
3.5.2 Vehicle Storage	146
3.5.3 Input Data	147
3.5.4 Text of Program	150
3.5.5 Procedures	151
3.5.6 Delay Storage	155
3.6 PROGRAM TESTING	156
3.6.1 Mechanical Tests	156
3.6.2 Calibration Testing	156
3.6.3 Running Times	156
3.7 PRODUCTION RUNS	
3.7.1 Constant Input Parameters	158
3.7.2 Simulation Times	164
3.7.3 Variable Input Data and Results	165
3.7.3.1 Starting Random Numbers	165
3.7.3.2 Effect of Section Length on Delays	165
3.7.3.3 Variation of Delay with Weaving Volume	168
CHAPTER 4 : EQUIPMENT	171
4.1 CAMERAS	171
4.2 INTERVALOMETERS	172
4.3 CAR FOLLOWING EQUIPMENT	172
4.4 PROJECTORS AND SCREENS	173
4.5 ACCELEROMETER	174
4.6 EVENT RECORDER	176
APPENDIX 1 : PROBIT ANALYSIS	177
APPENDIX II : ANALYSIS OF LAG ACCEPTANCE DATA	183
APPENDIX III : ANALYSIS OF GAP ACCEPTANCE DATA	185

	<u>Page</u>
APPENDIX IV : ANALYSIS OF GAP ACCEPTANCE DATA (ALL GAPS)	186
APPENDIX V : ANALYSIS OF GAP ACCEPTANCE DATA FOR GROUPS OF TWO VEHICLES	187
APPENDIX VI : EXAMPLE CALCULATION OF TRAFFIC SIGNAL SETTINGS	188
APPENDIX VII : SUMMARY OF INPUT CONDITIONS FOR TRAFFIC SIGNAL SIMULATION PROGRAM	192
APPENDIX VIII : GENERATION OF ENTRY SPEEDS	194

CHAPTER ONE : SIMULATION

The word 'simulation', when used in a general everyday sense takes the meaning

'to assume the appearance of'

(Shorter Oxford Dictionary)

It may also be used in a particular engineering sense, and HARLING (1958, ref. 1.1) has provided the following definition:

' the technique of setting up a stochastic model of a real system which neither oversimplifies the system to the point where the model becomes trivial, nor incorporates so many features of the real system that the model becomes untractable or prohibitively clumsy.'

The model may be set up in a number of ways, but the main purpose of any kind of model is to enable quick, convenient and reliable predictions of the effect of any design or design changes to be made.

1.1 METHODS OF SIMULATION

1.1.1 Physical Models

Physical models, which are familiar to most people, consist of a representation of the real life mechanism in the same or different materials to a more convenient scale or form. Examples are commonplace, and may include hydraulic models of dams, river estuaries and barrage schemes; model aircraft in wind tunnels, and model structures. They are only of use where any effect caused by the change of scale is predictable (which may be a considerable problem in fluid mechanics) and where measurement of performance can be arranged to be more convenient than on the prototype. They may also be restrictive in that changes in the form of the model to investigate the effect of alternative designs may be time consuming and costly.

An example of a physical model of a traffic situation is the work carried out by WARDROP (1957, ref. 1.2) at the Road Research Laboratory in an investigation into the capacity of weaving sections. In this case the model was actual size, and consisted of a weaving area set out on a large area of tarmac at Northolt Airport. The shape and size of the area were delineated with easily moveable concrete blocks, and the effects of any change in layout on the behaviour of traffic moving through the area were observed from steel towers. Use of physical models in traffic work is rare, however, large and expensive facilities being necessary.

1.1.2 Analogue Models

Some physical systems behave in a similar, or analagous, way to entirely different systems that are easier to handle. An example is the flow of water through a permeable soil and the flow of an electric current through a conducting medium such as Teledeltos paper. The paper is cut out in a shape that represents the shape of the soil layer under

investigation and an electrical potential applied to the region of high water pressure on the prototype. Use of a potentiometer and a moving probe enables the lines of zero potential to be quickly and easily plotted, whereas field measurement of pore pressures would be extremely costly and time consuming. In fact, this analogue model may be applied to any other form of Laplace field, such as stress in a plane layer or the flow of air around an aerofoil.

Electrical systems are particularly useful in analogue models because of their speed of operation, economy of size, and the ease with which values of potential, current and resistance may be measured: it is for these reasons that they are widely used. Analogue models suffer from two important disadvantages, however:

- i) Each of the interacting operations must take place simultaneously.

Although this makes for a high operating speed, it means that the more complex the prototype, the more complex must be the model.

- ii) The model is designed to simulate one particular kind of situation. If major changes in the mode of operation of the prototype are contemplated, the model must be redesigned.

Despite these disadvantages, HARTLEY et al. (1965, ref. 1.3) have designed an analogue computer for the investigation of several traffic situations. Vehicles are represented by identical voltage pulses. The arrival of vehicles at random is simulated by a 'Random Pulse Generator' giving Poissonian arrivals, which may be adapted to give mean arrival rates in the range 5 - 1350 veh./h. (Work is in hand at present - 1968 - to make other arrival distributions available). Binary counters are used to simulate waiting vehicles in queues and streets are represented by variable length delays. (The use of binary counters is, strictly speaking, a digital computer technique, and their incorporation

in this machine makes it a hybrid). A simulated fixed time traffic signal controller is available, and a variable queue extraction rate control to simulate saturation flows in the range 1200 - 2160 veh./h. The state of the model is monitored and displayed via meters and indicator lamps. Programming is achieved by patch-cord interconnections in a switching board.

Several traffic situations have been simulated, including an uncontrolled T intersection (ref. 1.4), traffic signals (ref. 1.5), gap acceptance at roundabouts (ref. 1.6) and a linked pair of intersections (ref. 1.7). Speed of operation is said to be comparable with digital programs of equal complexity - about 50 times real time (ref. 1.8) - making the system useful for on-line control in area control schemes (ref. 1.9). Another advantage claimed for the computer by the authors is that it is available at any time of the day or night, whereas simulation using an all purpose digital computer is restricted by the availability of that machine. Indeed, shortage of time on the University of Manchester's all purpose machine (Atlas) stimulated the development of the special purpose computer (ref. 1.3).

1.1.3 Mathematical Models

The stochastic nature of traffic means that the mathematical analysis of traffic situations is rather complex, and the mathematical techniques available at present limit the use of mathematical models to rather simple traffic situations on long, uninterrupted stretches of open road or at junctions.

TANNER (1962, ref. 1.10) developed a model for minor road traffic merging into a major stream. Both the major and minor streams were uni-directional, vehicles taking a finite time to move through the intersection, and arriving at random. A step function was used for the gap acceptance distribution, and Tanner developed an equation for the average delay per vehicle arriving along the minor road. MILLER

(1963, ref. 1.11) has developed a similar model, subject to similar restrictions, but using random bunches of vehicles, rather than individual vehicles. Neither of these two models consider the effects of vehicles turning right from the major stream into the minor road.

LITTLE (1961, ref. 1.12) proposed several models, one of which was used in an investigation into the problem of delay at fixed time traffic signals. Arrivals were at random and in a single lane, and the signal cycle was divided into effective green and effective red. The model could be extended to the two lane case for low and medium flows.

Many other authors have studied the problem including NEWELL (1960, ref. 1.13), HAWKES (1963, ref. 1.14) and DARROCH (1964, ref. 1.15), but a comprehensive review of literature on mathematical theories of traffic flow is beyond the scope of this work. Suffice to say that theories developed at present, because of the present limitations of available mathematical techniques, employ many simplifying assumptions that at best make restrictions on the use of the model, and at worst make application of the model impossible in even the very simplest traffic situations.

1.1.4 Digital Models

Digital simulation is a process which overcomes the objections raised in sections 1.1.2 and 1.1.3 in connection with analogue and mathematical techniques. The method is usually employed with the aid of a high speed, large capacity digital computer, but in fact, the machine merely makes the process much faster and is not essential to the technique. The basis of the method is that each quantity or parameter in the situation being analysed is represented by a number or variable. The situation is scanned at various time intervals and additions or subtractions made to or from each quantity according to certain logical rules which apply to the situation. That is, instead of connecting each of the variables by electrical circuitry or by an algebraic equation,

they are connected by a pattern of logic. The technique can be applied to any situation, simple or complex, and with varying degrees of accuracy. The only limitations are

- i) The amount of time available for computation.
- ii) The ability of the analyst to discover the logic pattern of the situation.

Fortunately, objection ii) is insignificant in most traffic situations, since traffic movements are subject to simple rules, even if the decision making process of individual drivers is not. However, in attempting to simulate, say, a national economy or the reactions of consumers to an advertising campaign, as has been suggested, objection ii) may become a serious obstacle. The techniques are explained more fully in section 1.2, but digital simulation overcomes the objection to analogue techniques - simultaneous interaction of all contributory factors - since each operation is performed consecutively. This merely means that the more complex the situation, the longer the computation time. Although digital computers are not essential to the process, the advent of such machines has made the process worthwhile, and converted an extremely lengthy procedure to a process which is usually faster than real time. It is also extremely flexible in that changes may easily be inserted into the controlling logic pattern (the program) - another objection to either analogue or mathematical models. Accordingly, the traffic situations described in the following chapters have been analysed by digital simulation with the aid of a high speed computer. A description of the methods employed is given in the rest of this chapter, together with a summary of other work in the field.

1.2 TRAFFIC SIMULATION BY DIGITAL COMPUTER

KELL (1963, ref. 1.16), concerned with the possible errors arising from random sampling of traffic data in the design or alteration of traffic facilities, defined what he considered to be the ideal capabilities of a traffic data collection scheme, viz:

- i) 'To be able to study enough hours of constant conditions to feel confident that the average result is a reasonable estimate of the average or mean of the entire distribution of values for that set of conditions.
- ii) To be able to request precisely the traffic conditions desired for the analysis.
- iii) To be able to change the control conditions easily and rapidly in an office situation rather than in the field.
- iv) To be able to reproduce precisely the same traffic under changed conditions.
- v) To be able to obtain large amounts of data in a relatively short time.'

The ideal, accurate simulation program should satisfy all these conditions, and indeed one other, which Kell has not stipulated, i.e. the ability to predict the performance of the facility under traffic conditions which do not presently exist, but are expected in the future.

The stages in the development of a simulation program have been listed by CONSTANTINE (1964, ref. 1.17):

- i) Analyse the traffic situation
- ii) Write computer program
- iii) Collect accurate field data to feed into computer

- iv) Carry out simulation studies
- v) Verify results of simulation.

1.2.1 Traffic Analysis

It is necessary to be able to break down the traffic situation into a series of simple logical steps which can be handled by the particular language being used. There are two approaches commonly employed: the macroscopic approach and the microscopic approach. In the former only groups or platoons are distinguished by the logic of the program, whilst the latter approach distinguishes and processes individual vehicles. Obviously the degree of accuracy to which results are required will dictate which approach is used. Usually the microscopic approach will require greater programming time and computer time, but will produce more accurate results: it is usually used in the study of single intersections. Where a whole area of streets and intersections is being simulated the macroscopic approach is appropriate. In this work the macroscopic approach has been used, since individual intersections were being examined in detail.

The procedure may be explained simply as follows. The investigator imagines himself to be suspended above the intersection with a camera, taking photographs of the traffic situations as they change and develop. He then 'describes' the situations as photographed within the computer by assigning values to various stores. Thus there may be a queue of three vehicles at the intersection, and he will assign the value 3 to the store he has designated to be his queue. After a certain time interval another vehicle may arrive and join the queue. He will therefore add one to the store designated 'queue'. In short, he scans the situation at various times and changes the values in the stores according to the situation. He, via the program, may also make decisions based upon the stored information: whether or not there are any vehicles in the queue may cause one or another traffic situation to develop. The program, in addition to merely storing numbers in 'pigeon holes', is able to scan these pigeon holes, examine the numbers therein and act

accordingly. For example, the programmer may write

'If there are any vehicles in store no. 1,
subtract one from store no. 2; if not, add
one to store no. 3.'

The time intervals between each scan of the situation need not be constant: it is sometimes more convenient to scan from event to event, for instance, from the arrival of one vehicle to the arrival of the next. The decision of whether to use 'event to event' scanning or a constant scan interval is purely a matter of personal preference and the situation being analysed, for with judicious choice of the scanning interval there is no reason why one method should be much more extravagant with computer time than the other. The author found the constant scan interval method easier to program, and so used this approach. The length of scan interval chosen will depend upon the traffic situation and the frequency with which events are likely to occur. Under heavy traffic flows a short scan interval is advisable to avoid missing events - under light flows it may be wasteful of computer time, and accordingly the scan interval was made a variable within the programs, the value for any particular run to be read in as input data.

The traffic behaviour is best analysed by means of a flow diagram before writing the program in a computing language. A flow diagram is a diagram consisting of a matrix of boxes, and the boxes are of two main types:

- i) Decision box (conventionally shown as a diamond shape)
- ii) Instruction box (rectangle).

In the decision box a simple question is asked which requires a 'yes' or 'no' answer only, such as 'are the signals at red?' From each decision box must run two flow lines, one for the answer 'yes' and one for 'no'. These flow lines connect either with another decision box or

an instruction box containing one or more instructions for the computer. Only one flow line may enter and leave an instruction box. (An example of a flow diagram is shown on Fig. 2.16.) This diagram then provides a logical framework to guide the writing of the program in a machine compatible language.

1.2.2 KDF9 and Algol 60

Two computers were used in this work, one housed in the computing laboratory of the University of Newcastle upon Tyne, the other in the Computer Block of the University of Salford. They were both English Electric Leo Marconi KDF 9 high speed electronic digital computers with the following facilities (details shown in brackets apply to the Salford machine):

- i) Random access main store of 16384
(32 768) 48-bit words.
- ii) One (one) high speed paper tape readers
reading one inch, eight-hole paper tape
at 1000 characters/s.
- iii) One (one) on-line paper tape punch punching
eight channel tape at 110 characters/s.
- iv) One (one) interruption typewriter for
monitoring programs.
- v) Three (three) magnetic tape units using
 $\frac{3}{4}$ in. 16-channel magnetic tape operating
at a transfer rate of 40,000 char./s.
- vi) High speed, line-at-a-time printer
printing 1,000 lines/min. either off-
line or on-line.

- vii) Magnetic disc unit consisting of eight discs providing storage for 1,966,080 numbers. Adjacent access time is 30 millisecs, random access time 230 millisecs.

1.2.2.1 Main Store

This is the main working area of the computer and is sometimes referred to as a 'core-store'. Information is stored in the form of 'words' which are merely binary numbers, and each 'bit' or element of the binary number is stored by magnetising a small magnetic disc in one direction or another, depending upon whether the bit is 1 or 0. Each word is stored in a pigeon hole or 'address', and 'random access' means that words are available to be read or changed in any order desired.

1.2.2.2 Paper Tape Reader

This device reads information from paper tape and converts it into electrical impulses which are stored as words within the core store. Paper tape is a medium by which the programmer may communicate with the machine. The program, which is a series of instructions, is typed on a teleprinter (a Flexowriter), and each character typed is simultaneously punched according to a code into 1 in. paper tape.

1.2.2.3 Paper Tape Punch

This is a device that enables the programmer to extract information from the machine on paper tape.

1.2.2.4 Monitor Typewriter

This is a Flexowriter directly linked to the machine, which is not usually available to the programmer. It enables the operator to instruct the machine whilst a program is running, and any failure reports are printed out on this device.

1.2.2.5 Magnetic Tape Units

Any information which requires storage whilst other information is present in the main store may be stored on magnetic tape. The information may be a program or data, and the programmer may write upon, read, or erase on the tape at will. The disadvantage is that data must be read or written consecutively - if information previous to that currently being processed is required, the tape must be rewound, which is an extremely laborious operation compared with the speed at which the computer operates.

1.2.2.6 Line Printer

This is merely a very fast printing device. Its speed is obtained by printing a line at a time instead of each character individually. 'Off-line' and 'on-line' in the context of input and output devices means that the device either handles the data whenever it is required by the program (on-line), or that data destined for the device or from the device is temporarily stored on disc or magnetic tape to be directed to the device when it is available (off-line). The latter facility is extremely useful when the computer is operating in the 'time-sharing' mode, i.e. operating on two or more programs simultaneously, when it may happen that a particular device is required simultaneously by the two programs. The device may then be used on-line for one program and off-line for the other.

1.2.2.7 Disc Unit

This device consists of a stack of eight discs and its function is similar to that of the magnetic tape unit. Information is read or written by a combined reading and writing head which can be dropped anywhere on any of the discs, so 'random access' is available, thereby overcoming the principal disadvantage of the magnetic tape unit. (It was available only on the Salford machine.)

Section 1.2.1 described the formation of the flow diagram. When this has been finalised it must be presented to the computer in the form of a series of switching instructions (machine code) to enable the data to be processed. Since these switching instructions require an intimate knowledge of the workings of the machine, it is obviously impracticable to expect occasional users to use this method in writing their programs. Accordingly programming languages have been developed. A programming language must be as convenient as possible to the programmer, yet concise and regular enough to be suitable for automatic translation into machine code. Several languages have been developed for this purpose, e.g. FORTRAN, Mercury Autocode, Atlas Autocode, PL/1, but the language usually employed in university KDF9 installations is the KDF9 version of Algol 60, called simply KDF9 Algol (ref. 1.18). Algol 60 (ref. 1.19) is an algorithmic language devised by an international committee in Paris, 1960. The aim was to produce a universally accepted programming language suitable for handling numerical and scientific calculations (as opposed to commercial operations). It makes use of English words and arithmetic operators which make it at the same time simple to write and yet extremely powerful: it is not completely universal, however, in that it does not include any input or output procedures. This means that each manufacturer is left to define his own input and output procedures and sometimes impose limitations on some standard Algol 60 procedures. Hence the need for a KDF9 version.

The program, written in KDF9 Algol and punched onto paper tape, is read into the machine via the tape reader and there it is automatically translated into machine code by another program called a 'compiler'. Two Algol compilers are available to users of KDF9 installations at universities: Whetstone Algol compiler (WALGOL) and Kidsgrove Algol compiler (KALGOL). The two compilers serve different purposes. WALGOL is used for testing ('debugging') freshly punched programs, and provides detailed and extensive failure reports. The compiling time is relatively fast, but actual computing (or run) time slow.

KALGOL is used in the POST system: POST is a system for handling programs which have been stored on magnetic tape. The procedure is as follows:-

- i) The program is written and punched in KDF9 Algol.
- ii) The program is tested using the WALGOL compiler and corrected if necessary.
- iii) If the program is to be required many times in the future, it is then 'established' in its KDF9 Algol form, i.e. copied onto a magnetic tape.
- iv) This copy is then translated into an 'optimised' form of machine code by the KALGOL compiler. (This is a fairly lengthy process - of the order of 20 minutes.) The highly efficient version of the program is then stored on another magnetic tape.
- v) When the program is required it is called down from the magnetic tape unit in its compiled form into the central processor, and run.

Since the KALGOL compiler produces a more efficient translation, the programs run much faster - as much as fifteen times - than the WALGOL translated version. By storing the translated version on magnetic tape the lengthy compilation time with the KALGOL compiler is performed only once, not each time the program is run, as with the WALGOL compiler. Scant information is available in the event of a failure, however, so the program must be correct before it is established to avoid laborious searching for mistakes.

Various specialised simulation languages have been written, such as

SIMSCRIPT, developed by the Rand Corporation (ref. 1.20), and GPSS - General Purpose Systems Simulator (ref. 1.21) developed for the IBM 7090 machine. These languages require special compilers which were not available to the author and which precluded their use. Algol is a sufficiently powerful language in any case to make programming simple: the time consuming parts of the work were found to be the construction of the flow diagrams and the correction of mistakes in the programming ('debugging'), neither of which would be eliminated by using these special languages. A 'Simulation Package' has been developed by PARSLOW (1965, ref. 1.22), and used by DICK (1967, ref. 1.23) which was designed to make programming easier in Algol. It provides a number of facilities common to all simulations, e.g. initiation of actions and their cancellation after a preset time or when certain conditions are satisfied. Occurrences are fed into a matrix, and this matrix and another data matrix are consulted after each event. The next event is found, operated upon and the time updated (event-to-event scanning). Unfortunately, the traffic signal simulation work was well in hand when the package was made available, and so it was not used. The weaving simulation, because of its essentially linear nature, was not suitable. It would seem, however, that the package might save considerable programming time for the more formal kinds of simulation such as the arrival of dock traffic, airports etc.

1.2.3 The Monte Carlo Technique

Simulation is a logical rather than mathematical method for dealing with problems whose formation is so complex that a useful mathematical solution is unobtainable. At the heart of the method is the so-called 'Monte Carlo' or random sampling technique, which deals with the problematical probability distributions encountered in traffic analysis. It is best explained by means of an example. Suppose the length of the next gap in the traffic stream is required by the program. If the

cumulative probability curve of gap lengths at a particular site is plotted (fig. 1.1), by generating a random fraction between 0 and 1 and moving across to the curve we may find the length of the next gap. Since the random fraction has an equal probability of falling anywhere between 0 and 1, if enough random fractions are generated the cumulative curve will eventually be reproduced. The cumulative curve may either be stored within the machine as an algebraic expression, or as an observed distribution. Obviously the former is the more economical method, but it is not always possible to achieve (ref. 1.17). This random selection process may be used for speeds, arrival gaps, vehicle lengths, or any other quantity expressed in the form of a distribution.

1.2.4 Random Number Generation

It is only possible to generate truly random numbers by observing some kind of physical mechanism, such as spinning a wheel, throwing a die or observing the number of gas molecules impinging upon a unit area in unit time, as is the method employed by the G.P.O. in the Premium Bond Lottery on ERNIE at Lytham St. Annes. Such methods are inconvenient for use on a digital computer, and mathematical techniques have been developed for the purpose. Since they are mathematical it follows that they must produce numbers which are predictable: the term 'pseudo-random' is therefore applied. A series of pseudo-random numbers is a series of numbers which are connected by some mathematical formula, and are therefore predictable one from the other, but which behave as if they are random.

There are several pseudo-random number generation techniques (ref. 1.24), a simple example of which is the Mid-Square technique, where a p -digit number is squared producing a $2p$ -digit number. The middle p digits are taken as the next number and the process repeated. A similar method is the Mid-Product method, where two starting numbers are taken (x_1 and x_2) and their product (u) is formed. The mid digits

of u are used to form x_3 , and the process repeated for x_2 and x_3 . There are two points to check when using a random number generator:

i) Does the series repeat, and, if so, after how many iterations?

ii) Is there any bias in the numbers generated?

The two simple examples quoted do have bias towards lower values, and so more sophisticated techniques have been developed. The method used by the author is that suggested by BEHRENZ (1962, ref. 1.25) and is shown as a flow diagram in Fig. 1.2. The first time the procedure is entered, a starting random number must be specified which must be less than 2^{35} . Thereafter this number must be replaced by zero, whereupon the procedure uses the last number it generated to form the next one, the cycle being repeated every 2^{33} iterations. If it is required to interrupt the series and start afresh with a new starting number, the zero in the procedure specification is replaced by the new number.

Also in the procedure specification must be the upper and lower limits of the range in which the number is to be generated (the Algol text of the procedure is shown near the beginning of the programs in chapters 2 and 3 with the heading 'Real Procedure Random (a,b,x0)'). Behrenz has checked the generator for bias, as have LAUGHLIN and POORE (ref. 1.25), and the results are shown in Table 1.1. No investigation of verification of the procedure was made by the author, in view of the work of these three authors.

The fact that a pseudo-random generator obviates the need for storage of random number tables is not the only advantage of the method: the fact that the generated series is repeatable, which at first sight may seem a disadvantage, is a very useful facility. It enables precisely the same traffic conditions to be repeated under differing control conditions, making very close comparison possible without differences due to random fluctuations confusing the issue. It may be emphasised though, that extreme caution must be exercised in interpreting the results of such comparisons.

1.2.5 Field Data

For the model to be as accurate as possible, field data should be collected and analysed for each aspect of traffic behaviour in the model. These may include

- i) Gap acceptance behaviour
- ii) Arrival distributions
- iii) Speed distributions
- iv) Acceleration rates
- v) Queueing behaviour
- vi) Pedestrian behaviour, if any
- vii) Range of parameters over which the above apply.

All the above should be observed, where possible, over as wide a range of traffic densities as possible, in order that the model may be regarded as being representative over this range. The usual methods of data collection in traffic engineering may be used, but a particularly useful method for this kind of work is the technique of time-lapse cinematography. The method has many advantages over more conventional methods, and these are discussed in Chapter 4, but the close analogy between scanning with a constant scan interval in the model and the data obtained by this technique aids understanding of the traffic behaviour considerably. The requirements are:

- i) A suitably adapted cine camera
- ii) A device to trigger the shutter of the camera at a constant time interval
- iii) A site for the camera.

The film thus obtained is then brought back to the laboratory to be analysed at leisure, and the results of the analysis used as input to the model.

1.2.6 Testing the Model

A simulation model which has not been tested and shown to be accurate is of limited value. Tests may be of two kinds. It may be possible, by using a particular combination of data, to produce a traffic situation which is easily analysed by theoretical methods, thus providing a check on the model's performance. In a study of the influence of turning traffic on saturation flow at traffic signals, as described in Chapter 2, for instance, the results of a simulation involving no turning vehicles is predictable. It is impossible to generalise because so much will depend upon the structure of the model and what it is designed to do, but the programmer should have no difficulty in designing such tests for his own particular model.

The other method of testing is to feed in observed traffic data such as turning movements, arrival rates, signal timings, etc., and to check that the performance of the model corresponds to the observed performance of the prototype. A measure of performance in the case of a signalised intersection might be saturation flow values which have been observed concurrently with the input parameters. If this process is repeated over a wide range of conditions, so much the better, but this may be difficult to achieve in practice.

1.2.7 Simulation Studies

The optimum running time for the program must be found. Differences due to the use of different starting random numbers will arise, and the program must be run for a sufficiently long time for these effects to become insignificant. It may be that the model starts 'empty', and the program must allow time for queues etc. to fill up and the effect of this 'starting error' to reduce to negligible proportions. The optimum running time will be the shortest running time that reduces these two errors to acceptable levels.

1.3. - SOME SIMULATION MODELS

1.3.1 Early Work in the United States

The first work in the field of traffic simulation was that by MATHEWSON et al. (1955, ref. 1.26). Their model was of a four arm signalised intersection with single approach lanes and with provision for pedestrians. Left turns were permitted, but no right-hand filtering was allowed (right-hand rule of the road). Arriving vehicles entered an initial waiting zone, and if the signals were at red or the vehicle ahead had been delayed, the arriving vehicle was also delayed. On exit from this zone (on the clearance of the vehicle ahead) a direction selector selected a turning movement for the vehicle: if it was designated a straight ahead vehicle, it proceeded through the intersection without delay; if a right turner, it may have been delayed by pedestrians; if a left turner, by pedestrians or oncoming traffic. Three modes of simulation were considered: a discrete variable simulator, a continuous variable model, and a model for a general purpose computer. The first two kinds were analogue models using electrical circuitry in the Standards Western Automatic computer, the logic being represented by counters, and 'and-gates', 'or-gates' and 'and-not gates'. (The gates correspond to 'decision boxes' on flow diagrams and are able to switch impulses through alternative circuits on receipt of pulses from other 'informatory' circuits). In the first model the vehicles were treated individually and represented by pulses. Vehicle arrivals were received from a random pulse generator, and the vehicles were transmitted or obstructed by the gates according to signals received from the 'interference generators', which represented pedestrians, oncoming traffic, or signal controllers.

The second, continuous variable, model was designed for approximate studies on a large network, and continuous voltages instead of pulses were used. Discharges from the various discharge points such as stop-lines were allowed at a rate inversely proportional to the voltages

transmitted by interference generators, and delays due to journeys along streets were represented by magnetic tape moving at a constant speed past a recording head and a reading head, separated by a distance proportional to street length.

The third, and last, approach considered by the authors was a model suitable for use on a general purpose digital computer. Streets were divided into m blocks of one car length and represented by a binary number. If a vehicle was present in a particular block, a 1 was inserted in the appropriate position, the other empty blocks being represented by 0. By performing arithmetical operations on the 'streets', the 1's were moved from block to block. For example, by multiplying the 'street' by 2, the vehicle was moved one block. In binary arithmetic,

$$\begin{array}{r}
 00000001000 \\
 \times 10 \\
 \hline
 = 00000010000
 \end{array}$$

No details are given of the performance of any of the three models, but the authors point out that, despite the high speed of the computer (one addition in 64 microseconds), the simulation may be slower than real life, owing to the large number of computations to be performed. (Present day computers are, of course, much faster than SWAC, the computer used in this work. KDF9 performs one addition in 1 microsecond.)

GERLOUGH (1956, ref. 1.27) developed the binary number device further in a later paper. Again written for SWAC, the model was of a two-lane one-way road. Vehicles entered the system at time spacings sampled from either an observed distribution or a theoretical distribution. A speed distribution was assumed and it was also assumed that no vehicle required to travel faster than that at which it entered the system: vehicles were delayed, however, by slower vehicles ahead of them. A safe following distance was defined which could be a constant, a random variable, or a function of speed. When this safe following distance was

encroached upon by the following vehicle, the following vehicle moved into the left hand lane (right hand rule of the road), provided it was safe for it so to do. If not, the following vehicle decreased its speed in steps until it reached the speed of the lead vehicle. Once past the overtaken vehicle, the right hand lane was examined, in order that the overtaking vehicle might move back and continue at its entry speed. The vehicles were checked every scanning interval to see if it was possible for them to return to their entry speed. Again, the vehicles were represented by the figure 1 in a binary number, and it was possible to join several numbers to form longer lengths of road. Supplementary information such as entry speeds and safe following distances were carried in parallel numbers alongside the number representing the street. Vehicles were moved by binary multiplication in increments of one vehicle length. Suggested lines of investigation for which the model was suited were investigations into the

- i) Average time for a vehicle to traverse the system,
- ii) Proportion of vehicles which are delayed,
- iii) Average delay,
- iv) Number of lane changes/s,
- v) Total delay.

A mathematical representation model was also proposed. The 48-bit word was broken down into sections, each section carrying a value representing location, lane, present speed, desired speed and vehicle length. The location was changed every scan interval by multiplying the actual speed by the scan interval and adding the result to the value currently held in the location store. (These proposals laid the foundations for the weaving model described in Chapter 3).

The binary arithmetic model was run on SWAC for a $\frac{1}{4}$ mile section

with 1/16 mile sections at each end to eliminate end effects. No results are reported in the paper, but they are said to be 'qualitatively consistent with what might be expected, in the absence of comparative field data'. Simulation time was 35-38 times real time.

GOODE et. al. (1956, ref. 1.28) developed a more sophisticated model of a signalised intersection than that described in ref. 1.26 at the Willow Run Research Centre of the University of Michigan. Included in this paper is a table (reproduced in Table 1.2) which is an interesting attempt to justify simulation as a method of analysis. The model was designed for use on a MIDAC digital computer, and was intended to be a typical intersection. The original intention was to build up a series of these intersections with roadway links to investigate traffic behaviour, but the work did not progress further than one intersection. The authors specified the following features for their typical intersection:

- i) Four approach arms 400 ft. long and 22 ft. wide
- ii) Vehicle lengths ranging between 11 and 22 ft. with a mean of 18 ft.
- iii) Unobstructed vehicles travelling at 30 mile/hour
- iv) Three phase fixed time traffic signals
- v) Left and right turns permitted
- vi) Negligible interference from parked vehicles and pedestrians.

The lanes were represented by lines, and spaced along each line were 40 points: vehicles jumped from point to point as they progressed along the street. For each lane there were four vehicle paths: one for right turning vehicles (right hand rule of the road), one for straight ahead vehicles and two for left turning vehicles, one of which ended in a left turning zone. Each vehicle jumped one point per quarter second,

and speeds were made typical for that path by varying the distance between the points. The positions of the vehicles along the paths were again represented by 1's in a binary number which in this case was 44-bits (digits) long - more than enough for the 40 points on each path - and vehicles were always separated by at least one zero, because the length of the shortest vehicle (11 ft.) was equal to the greatest separation of the points ($\frac{1}{4}$ sec. @ 30 mile/hour = 11 ft). Vehicle arrival gaps, lengths and turning movements were obtained using a pseudo-random number generator and random sampling, and if any vehicle arrival gap was less than $\frac{1}{4}$ s., the vehicle was stored in a waiting zone. The signal timings were variable with a fixed amber time of 3 s. Vehicles were allowed to turn left (right hand rule of the road) provided that no previously turning vehicle blocked the turning area, and provided that oncoming traffic was at least 55 ft. away. (55ft. at 30 mile/hour is 1.25s. - an unrealistic figure for this manoeuvre. The 55 ft. was based on a safe following distance when both vehicles were travelling at 30 mile/hour. (See section 2. on gap acceptance.) Average delay per vehicle was investigated and plotted against cycle time, proportion of turning vehicles, green time and volume, 'delay' in this work being the time taken to traverse the intersection minus the minimum time required to execute this manoeuvre. The MIDAC computer simulated the intersection at 3.2 times real time, but the authors say that this performance could be much improved by using a larger machine and more sophisticated programming techniques.

1.3.2. Early Work at the Road Research Laboratory

HILLIER et. al. (1954, ref. 1.29) made the point that delays at traffic signals are difficult to measure owing to large random fluctuations in traffic conditions, and developed a computer to simulate vehicle arrivals at traffic signals in an attempt to overcome the problem. The computer was named the Automatic Delay Computer (ADC) and was constructed in the main from standard electro-mechanical Post Office telephone equipment. A fixed time effective green/effective red signal controller was simulated

with each approach being considered in turn rather than simultaneously. The delay experienced by vehicles was defined as the difference in time taken by an uninterrupted vehicle to traverse the distance between the point reached by the end of the longest expected queue and the stop line, and the time taken by a queueing vehicle to traverse the same distance. Vehicles were subtracted from the queue at the average saturation flow rate appropriate to the simulated arm during the effective green time: presumably the effect of right turning vehicles was allowed for in the calculation of the saturation flow rate, but this is not specifically stated in the report.

Vehicle arrivals were input to the computer on 5-hole paper tape, and three methods were employed:

- i) Actual measured vehicle headways
- ii) Calculations made from random number tables
- iii) Calculations made by a random number generator on a Ferranti computer.

Four channels were used for vehicle arrivals, and the fifth supplied a time base. A portable tape punch was developed for use with method i) enabling on-site observations to be punched directly onto the tape. The punch could be used either to record arrivals on four arms simultaneously, one channel per approach or, when used on one approach only, vehicle arrivals corresponding to $2\frac{1}{2}$, 5 and 10 percent increases in observed volumes were automatically punched on the three remaining channels. By judicious switching of the channel readers on the computer, increases in observed volumes up to $17\frac{1}{2}$ per cent could then be simulated.

The computer simulated the intersections three times faster than real time and the results agreed closely with observed results. The success of the work led to the development of a simulation model for use on the pilot A.C.E. computer at the National Physical Laboratory, reported by WEBSTER (1958, ref. 1.30). The simulation was identical

to the work on the ADC, but this time modelled in software, and the work led to the development of the well known Road Research Laboratory formula for the average delay/veh. at traffic signals reported in ref.

1.30. The intention then was to develop a similar model using a model of a two phase vehicle actuated controller (ref. 1.29 p.5), but the work was not continued. BENSON (1962, ref. 1.31) developed a program to model a vehicle actuated controller on Pegasus II, but, again, the work was not continued. Since 1960 the Laboratory's simulation work has concentrated on linked traffic signals (ref. 1.32) and uncontrolled intersections (ref. 1.33).

Since the early work described above in sections 1.3.1 and 1.3.2, a great deal of work has been done both in this country and the U.S.A. on simulation, and as computing machinery and techniques have advanced so has the ease with which the traffic engineer, as opposed to computing engineer, can apply himself to the method. Because of the great volume of published work on this topic, no attempt has been made to follow its chronological development any further, but rather to concentrate on the major contributors to this still expanding and developing technique.

1.3.3 On-Ramp Models

WOHL (1960, ref. 1.34), working at the Massachusetts Institute of Technology developed a model to simulate traffic merging from an on-ramp into the freeway traffic. The aim of the study was to discover the average delay to merging vehicles and the capacity of the ramp. Various simplifying assumptions were made:

- i) Random arrivals along the freeway
and at the ramp with a minimum headway.
- ii) Priority (i.e. no delay) to freeway
vehicles.
- iii) No lane changing within the ramp
vicinity.

- iv) A distinction was made between stopped vehicles and the merging gaps they require, and moving vehicles and the merging gaps they require (see Section 2 for a more detailed discussion of this topic).
- v) Various delays to stopped merging vehicles to allow for acceleration time according to their queue position.

Fig. 1.3 is a diagram of the merging situation. On the arrival of a ramp vehicle at the nose of the ramp the next freeway 'lag' was computed. (A lag is the time difference between the arrival of a ramp vehicle and the next freeway vehicle at the nose of the ramp.) If this lag was greater than the lag that all moving vehicles would accept, the ramp vehicle was considered to have merged. If not, an acceptable lag was found by random sampling from distributions observed by WYNN et al. (1948, ref. 3.19). If the available entrance lag (see fig. 1.3) was smaller than the minimum acceptable lag sampled from Wynn's low relative speed distribution, the ramp vehicle was considered to have stopped. The next freeway arrival gap was examined and a similar routine employed, but this time selecting the acceptable entrance gap from a high relative speed distribution. If acceptable, the ramp vehicle moved off with a departure time three seconds later than the arrival time of the lead freeway vehicle defining the acceptable gap, to allow for starting delays and minimum following distance, and a further 5s were added for acceleration delays (i.e. the delay to a stopped ramp vehicle was eight seconds plus the time spent queueing and waiting for a suitable gap). The next vehicle in the queue was then examined and was treated as a low relative speed vehicle until it was stopped at the nose.

The program was run on an IBM 704 computer for various levels of freeway and ramp volume, and the average delay/veh. plotted. At the time of writing (April, 1960) the results had not been tested against observed field data, but the author emphasised the importance of so doing.

It was intended to modify the program so as to accept any distribution of arrival gaps and to provide more detailed descriptions of delays, and to investigate the dependence of minimum acceptance gaps on freeway and ramp volume. The results of these investigations have not, to the author's knowledge, been published. Using the IBM 704, 400h. real time was simulated in 50 min. of computer time, which is a considerable improvement over the early work described in the previous two sections.

PERCHONOK et al. (1960, ref. 1.35) working at the Mid-West Research Institute, Kansas City, produced a more detailed on-ramp model backed up by a considerable amount of field observations observed at four major Chicago interchanges. The information was coded and punched onto cards, and each of the 20,000 cards contained information about the vehicle type, its longitudinal and lateral position in the ramp area, the time it passed the recorder (some recorders were automatic and the others manually operated), and the time that the previous vehicle had passed the recorder (so that the time gaps could be obtained). The cards were processed on an IBM 709, and the information extracted included:

- i) Headway distributions. (It was found that the exponential distribution was accurate for volumes up to 275 veh./h.)
- ii) Acceptable gap distributions in the form of step functions for different relative speeds. (These distributions were not particularly well defined.)
- iii) Speed distributions, which were found to be normal, if rather peaked. The coefficient of variation was found to approach 0.1 as the flow in any particular lane approached capacity

- iv) The proportion of freeway traffic in each lane. This was found to vary with the proximity of on/off ramps, signs, and the physical characteristics of the site.

The simulation model was then designed using the field data as a basis for decisions. The ramp area was set up in a 4×100 matrix, the rows representing three freeway lanes and the on-ramp, and the columns representing blocks 17 ft. long - the average vehicle length. (Fig. 1.4 shows the arrangement.) Point D, the end of the acceleration lane, was moveable by adjusting the values of m and n , but point c, the ramp nose, was stationary. The initial 30 columns of the freeway and 5 columns of the ramp were stabilisation zones, and each block was scanned each second of real time: if a particular block was occupied the vehicle was moved according to a set of rules set out in the flow diagram and based upon the field observations. 100 s of real time was allowed for stabilisation and the entry of vehicles to the system, and then results were recorded for the next 200 s. This operation required 30 s of computer time - a 10 : 1 ratio. Acceleration began on the ramp as the vehicle found a suitable gap, and was added to the vehicle's ramp speed at a rate of 3.4 ft./s^2 for 4 s in the case of a merge by a moving vehicle, and added to half the vehicle's desired ramp speed at a rate of 5.1 ft./s^2 for 10 s in the case of a slowed vehicle.

The main conclusion reached in the work was that the extension of the acceleration lane of 595 ft. to 765 ft. reduced delay to ramp vehicles by only 0.001 s/veh. - an insignificant improvement, although this result has yet to be verified on the ground. However, an extremely useful model was developed and made all the more valuable by the great amount of field data.

DAWSON et. al. (1965, ref. 1.36) were commissioned by the Committee on Highway Capacity of the Highway Research Board to design a model to investigate the effect of 'yield' signs at on-ramp exits. They defined

the capacity of on-ramps in terms of waiting times and queue lengths, and analysed two types of on-ramps:

- i) with an acceleration lane and no sign control,
- ii) with 'stop' or 'yield' signs but no acceleration lane.

In both cases the single lane on-ramp was 16 ft. wide and merged with a three-lane freeway. The acceleration lane was 12 ft. wide and 450 ft. long with a 300 ft. taper. All vehicles were assumed to be 16.5 ft. long passenger cars with acceleration and deceleration potentials of 5 mile/h/s (7.33 ft./s²) and 6 mile/h/s (8.8 ft./s²) respectively, and all drivers were assumed to have a reaction (PIEV) time of 1.5 s. The minimum time headway on the freeway was set at 0.5 s, 2.0 s on the ramp with 'stop' or 'yield' control and 1.8 s on the ramp with acceleration lane.

Two types of gap acceptance models were proposed:

- i) For the on-ramps with no acceleration lane,

$$P(t) = 1 - e^{-\frac{t - t_{\min}}{\bar{t} - t_{\min}}}$$

where $P(t)$ = Probability of acceptance of a gap of length t .
 t_{\min} = Minimum acceptable gap.
 \bar{t} = Average acceptable gap.

- ii) For the on-ramp with an acceleration lane,

$$P(t) = \log\left(\frac{t}{t_{\min}}\right) \times 1/\log\left(\frac{t_{\max}}{t_{\min}}\right)$$

where t_{\max} = Minimum gap length for which the probability of acceptance is unity.

Distinctions were drawn between stopped, first-in-line, and moving vehicles. Arrival gap distributions were described by two models:

- i) Shifted exponential
- ii) Hyper-exponential (i.e. Schuhl's composite distribution - c.f. section 2.2.3).

Speeds, although known to be distributed normally on freeways, were generated using the equation

$$\text{Speed} = 52.0 - 0.008 \times \text{shoulder lane volume}$$

and assumed to be constant at 30 mile/h. on the ramp. The gap acceptance logic was constructed for two cases: in the case of 'stop' sign control, the ramp vehicle drew to a halt at the stop line, waited for an acceptable gap, and then accelerated away. Where there was a 'yield' sign or acceleration lane, the situation was considered to be more complex, but was resolved by assuming that the driver would stop at the stop line unless a gap was available which would enable him to travel at his desired speed.

The program was written in FORTRAN IV, and no measurements of delay or queue length were taken while the first 300 vehicles were arriving in the system. Measurements were taken on the next 1,000 vehicles, but this figure was based upon the cost of computer time, rather than any sampling theory. About half the computer time was used in preloading the system, initialisation routines and output, and analysis of results, producing a simulated time/computer time ratio varying between 30 : 1 to 360 : 1 on an IBM 7090 computer.

The results obtained in this study proved extremely worthwhile, but they are really irrelevant to this work: suffice to say that delays were greatest with 'stop' sign control and least with the acceleration lane. It is not apparent from the paper whether these results have been checked in the field.

No work has been published in this country yet on the simulation of on-ramp areas, presumably because of the shortage of urban motorways actually constructed. As urban traffic becomes more intense, however, investigators in this country will no doubt find the technique as useful as have their North American counterparts.

1.3.4 Single Traffic Signal Controlled Intersections

KELL (1962, ref. 1.37, 1.38, 1.16) working at the Institute of Transportation and Traffic Engineering, California, suggested that as a first step in analysing a network of streets by a macroscopic simulation technique, the individual intersections themselves should be analysed microscopically in order that the principal factors affecting delay may be ascertained. Accordingly, he started the work by simulating on a microscopic scale an individual four-arm intersection controlled by 'stop' signs on two of the arms. The intersection was orthogonal, and composed of two, two-lane, two-way streets. Vehicles were introduced to the system at a point far enough back from the intersection so as to be unaffected by the intersection, and the arrival gaps were generated by random sampling from Schuhl's composite exponential distribution. A separate random number generator was used for each approach, and the author describes an iterative technique for the fitting of the distribution to observed field data. Each vehicle was randomly assigned a turning movement according to the required turning volumes at the generation point. Minor street vehicles travelled through the system and were stopped either at the stop line or the end of a queue. Thereupon they waited for an acceptable gap, the next gap in the major stream was examined and the procedure then was as follows:

- i) Bissell's (ref. 2.24) log. normal gap acceptance curves were examined and the probability of acceptance appropriate to the gap size was found,
- ii) A random fraction was generated,
- iii) The gap was judged to be accepted or rejected by comparing the results of (i) and (ii).

This procedure was repeated for the next gap if the first was rejected.

The author points out that this procedure could result in a driver eventually accepting a gap smaller than one previously rejected, but justified this apparent anomaly by saying that Bissell observed this phenomenon on 5% of occasions. The number of occasions upon which it occurred in the simulation was not reported.

Major road vehicles passed through the intersection undelayed unless obstructed by turning vehicles, turning vehicles being decelerated (or accelerated) at 5 ft./s^2 to 8 and 9 mile/h for right and left turns respectively. Unobstructed turning vehicles were not considered to have been delayed, but a vehicle forced to decelerate for any other reason was so judged. Delays were summed for each approach and printed out at the end of the run. The author mentions the difficulty in random sampling of traffic volumes in that generated volumes tend to be different from requested volumes. He overcame the problem by choosing his starting random number so as to generate precisely the requested number of vehicles in the simulation time required. Event-to-event scanning was employed, and the program was written for an IBM 701. 12000h traffic was simulated in 30h, giving a simulated time/computer time ratio of 40 : 1. At the end of the simulation some gaps in the information were apparent but it was impossible to repeat any runs because of administrative reasons. Total delay for various major and minor street volumes were plotted. Surprisingly, delay to major street vehicles increased as the minor street volume increased.

The traffic signal model was designed for use on an IBM 7090 computer, and the intersection modelled was similar in all respects to the model described above, apart from the traffic signal control. Initially, a fixed time controller was simulated with a 60 s cycle time, and two timing plans were used:

- i) Constant 50%/50% split in effective green times.

- ii) Green times set according to the ratio of the heaviest flows on the major and minor approaches (saturation flows being the same for each approach).

Later different cycle lengths, and then a vehicle actuated controller were simulated. The results for the vehicle actuated controller have not, to the author's knowledge, been reported. About 40,000 hours of traffic were simulated and reported upon, split equally between

- i) The stop controlled intersection
- ii) Fixed time constant 50/50% split traffic signals
- iii) Fixed time volume sensitive green times.

The size and off-line input/output facilities of the IBM 7090 computer enabled extremely fast simulation times to be achieved - a simulated time/computer time ratio of 7000 : 1 was reported - and a large amount of information was presented about the effect of signal timings upon delays.

Some five hours of actual traffic conditions were observed as a check for the model, and observed and simulated total delays were compared. The observed delays were reported to be well within the scatter encountered in the simulated results.

An extremely ambitious and comprehensive simulation project commissioned by the National Co-operative Highway Research Program has been reported by GERLOUGH et. al. (1965, ref. 1.39). The aim of the study was to investigate the effect of various control schemes for signal controllers at individual intersections, and it was decided that a simulation technique would be the best approach. A comprehensive literature survey revealed

gaps in the necessary field data such as lane distribution, and where they occurred data collection exercises were carried out. The model was of a four-arm intersection of one, two or three lane approaches as necessary. It was a microscopic simulation which dealt with individual vehicles, their behaviour being described by car-following theory. At entry to the system each vehicle was assigned a group of parameters sampled by random sampling from distributions obtained from the literature survey or the author's own field work. The parameters included

i) Acceleration and deceleration potentials

ii) Reaction times

iii) Target (desired) maximum velocities

iv) Lag and gap acceptance requirements.

Each vehicle was followed through the system, its behaviour being simulated in fine detail, and the model included a lane switching facility whereby a straight ahead vehicle arriving at the end of a queue of left turning vehicles could change to a clear lane. The scanning interval was variable between 0.25s and 0.50s. The authors found that if the scanning interval was set at less than 0.25s the simulation became wasteful of computer time, and if at greater than 0.50s it became too coarse. They recommended that the scanning interval be set at half the minimum reaction time.

The program was written in FORTRAN 11 for an IBM 7090/94 computer, although the program is also compatible with IBM 709. Since the program is so detailed, a large storage area is required - 30,000 words. Again, because of the degree of detail, the program is quite slow to run, the simulated time/computer time ratio being about 5 despite the high speed of the IBM 7090.

The model was checked thoroughly against field data. Ten engineering technicians were employed and observed a total of eighteen hours of traffic behaviour at an intersection in Chicago in co-operation with the Chicago Area Expressway Surveillance Project. The traffic signal

controller, a model 1022, was linked directly via a multiplexing unit and a telephone cable pair to a CDC 160 digital control computer. Traffic behaviour was manually sensed by observers equipped with a bank of push button switches linked to the controller and thence to the computer. Traffic signal aspects were, of course, sensed automatically. Such items as

- i) Vehicle arrivals
- ii) Vehicle departures
- iii) Queue addition
- iv) Complete queue clearance

were observed manually, since the detectors could not be relied upon. The CDC 160 program stored the data as it came in over the telephone pair, registered the signal aspect, printed out queue lengths at 5 s intervals and when commanded by the operator, printed out the value of all the stores and set them up for the next data collection period.

Also, the CDC 160 could, when required, override the signal controller and set up control methods and policies similar to those tried in the simulation which were impossible to set on the controller. The field data collection exercises were carried out on six separate days. Comparison between observed field data and simulation runs showed that the central tendencies of the simulated quantities were accurate, but dispersions were consistently lower despite the high degree of non-homogeneity built into the model. Both the existing and experimental control policies were accurately simulated.

The aims of the project were three-fold. The first aim was to study the measures of effectiveness of intersection performance, such as average delay, which are difficult to measure in the field owing to the lack of knowledge of the vehicle's target velocity. Other parameters such as stopped delay are easier to measure but less useful as a measure of effectiveness. The second aim was to investigate new control policies

for intersections, and five such policies were tried. The authors stress at this point the advantage of simulation over field trials of the exact 'reproducibility' of the traffic demand whilst assessing the effectiveness of new control philosophies. The third and final aim was to assess the effectiveness of various phasing schemes in coping with turning traffic. The simulation produced a wealth of valuable information about traffic signal control which was

' derived in a relatively short time' and 'rather conclusively confirmed the appropriateness of the simulation approach and justified the time and energy spent in its preparation.' (p.7)

1.3.5 Linked Traffic Signals and Networks

GERLOUGH et al. (1962, ref. 1.40 and 1.41) developed a model to simulate the flow of traffic in traffic signal controlled networks. The model was macroscopic in that each link in the network was divided into zones, the length of a zone being proportional to the scan interval and the free flow speed of the traffic. The zones were further sub-divided into lanes, and the link was uni-directional: a two-way street consisted of two links, one in each direction. At each scan, four operations were performed:

- i) Vehicles were generated on the input links
- ii) Vehicles were moved (or not, according to the signal aspects) from the front zone of each link to the rear zone of the connecting link (defined as 'inter link movement')
- iii) Vehicles were advanced from zone to zone within the links (intra link movement).

iv) The signals were updated.

Vehicles were generated on the input links using the Poisson distribution, and it was possible to vary the generation rate on each input link at fifteen minute intervals of simulated time. Turning movements and lane positions were decided by random sampling, and inter link movements by the state of the signals and the state of the queues.

Six traffic signal states were available:

- i) Red
- ii) Full green
- iii) Green arrow (straight ahead)
- iv) Green arrow (left turn)
- v) Green arrow (right turn)
- vi) Green arrow (diagonal) (since same diagonal links were allowed).

The green signal aspects were available in any combination. Each zone was processed in turn and movements or delays (i.e. non-movements) were recorded. Since each zone could contain more than one vehicle, the model may be described as being macroscopic. Data on the spread of platoons and saturation flows were obtained using aerial photography, and on traffic speeds using the moving observer method. The model was tested against a fifty-four intersection network, and found to be satisfactory, but no details of running times and performance are reported in the references quoted.

FRANCIS et al. (1963, ref. 1.42) developed a similar type of program to that described above for use on a Ferranti Pegasus computer. The model was macroscopic in that the paths of individual vehicles were not followed by the model, but turning movements were assigned at the end of each link by random sampling. Each link had two parameters specified: the average speed on the link, and the range of speeds. At entry to a link the vehicle was assigned a speed from a distribution

specified by this mean speed (u) and range (R). The speed was generated by generating three random numbers (r_1 , r_2 and r_3) between -1 and +1, viz.,

$$\text{Speed} = u + \frac{1}{3} (r_1 + r_2 + r_3) \times R$$

This method is said to reproduce a speed distribution approximating to distributions actually occurring on urban streets. Although the authors give no further details, it is apparent that some care must be exercised when using this model. If it be assumed that the lowest speed that can occur is zero (obviously in practice this is unlikely), then this lowest value must occur when $r_1 = r_2 = r_3 = -1$. Therefore, we have:-

$$\begin{aligned} 0 &= u + \frac{1}{3} ((-1) + (-1) + (-1)) \times R \\ &= u - R \end{aligned}$$

$$\therefore R = u$$

i.e., if R is greater than u , then there is a possibility of generating negative speeds. Table 1.3 reproduces details of speed distributions observed on various categories of roads by the Road Research Laboratory. The categories were:

- A : High Street, 1952
- B : Inner Suburban Road, 1958
- C : Outer Suburban Road, 1958
- D : Rural Road, 1958
- E : Motorway, 1960. (Ref. 1.43, p. 105).

Inspection of these details reveals that the observed ranges are on three occasions greater than the mean speed, and that indiscriminate application

of the observed parameters to the model described above would lead to the generation of negative speeds. (The model is also explained in ref. 1.44 on page 143.) In private correspondence with one of the authors, it has been established that the model was in fact based upon data in which the greatest range was approximately 70% of the mean observed speed, and that therefore the problem of generating negative speeds did not arise.

The signal cycles were divided into effective green or effective red, the green time being specified for each link end at the beginning of the program. A vehicle arriving during the effective red or in the presence of a queue was stopped, but otherwise allowed to proceed. Queue extraction was achieved by the generation of a random number and comparison with the saturation flow input for the particular link end.

The program operated at approximately $(18/n) \times \text{lifespeed}$, where n was the number of junctions, and printed out at specified intervals.

- i) Simulated time
- ii) Flows in all links
- iii) Delays on all links
- iv) Delays at all junctions
- v) Average queue lengths on all links.

No mention was made of the accuracy of the model.

In an investigation into benefits that could be expected from computer control of a network of streets, GRIMSDALE et al. (1963, ref. 1.45) developed a microscopic model of a network of 19 roads and 9 traffic signal controlled intersections. In this model, unlike the two described above, vehicles were followed from entry to their desired exit. The roads were represented by $4n$ addressable locations (each road had four lanes) where n is the number of vehicles required to fill each lane of

the road. Vehicles entering the network were given identification numbers which specified their desired exit, but they were otherwise indistinguishable. A further important difference in this model and those of Gerlough and Francis is that, in the former, the road network was absolutely fixed, the only variables being control concepts and volumes, whereas in the latter, the network was specified by the input data.

Six separate phases were available for the traffic signals, and no time was spent by vehicles in crossing the intersections. The simulation, written for a Mercury digital computer at the University of Manchester, was achieved in four phases:

- i) Alteration, where necessary, of the signal phases
- ii) Generation of vehicles at the sources (no information is available about how this was achieved).
- iii) Movement of the vehicles across the intersections
- iv) Movement of the vehicles along the roads.

Two traffic signal control schemes were investigated:

- i) Fixed-time
- ii) Vehicle actuated.

Vehicle actuation logic in the model not only decided the duration of a particular phase, but whether it should be called. If the phase was not demanded by vehicles in the system, or it was not required by a different section of the control logic, it was not called. It became apparent during development of the model that some method of limiting

entry to the system would be required to avoid congestion, and three schemes were attempted:

- i) Entry limits were made equal but variable according to the degree of congestion
- ii) Entry limits at a particular entrance varied both according to the degree of congestion as a whole, and to the extent to which traffic from that entrance was estimated to contribute to the overall congestion
- iii) Entry limits equal and fixed at what was thought to be a good average flow rate.

A further refinement was the provision of route advisory signs, eighteen in number, which were changed when the average delay on one route differed by a fixed amount from a parallel route. The most successful control scheme was found to be vehicle actuation of the signals with route control and type ii) entry control. No performance details or field check data were given by the authors in the paper.

WATJEN (1965, ref. 1.46), working in Germany on the development of the IBM General Purpose Systems Simulator (GPSS) package, developed a very simple model to test the package. Three equally spaced intersections controlled by fixed time linked traffic signals and connected by a single lane were simulated, no allowance for platoon dispersion being made. The author reports that the model was simply set up using the package, which consists of blocks of pre-prepared programming. The main components are 'generate' or 'originate' blocks which generate Poissonian arrivals, 'queue' blocks and 'terminate' blocks which discharge vehicles from the system, and the blocks are connected by control logic.

Output of performance is available from any block at any time.

The model was run on an IBM 7090 machine giving a time advantage of 42 : 1 and the effects of different offset times on average delay per vehicle was investigated. The author reports close agreement with other published work.

The last paper to be reported in this by no means comprehensive review of traffic signal system simulation is a model developed by CRAFT et al. (1967, ref. 1.47). It was set up using a simulation package developed by Plessey Company and was designed to study the effect of different timing plans on a linear route of up to 25 intersections. Entering traffic was generated by random sampling from negative exponential distributions at the ends and on the cross arms. Vehicles entering on the cross arms were allotted a turning movement by random sampling, but after entering any particular link, vehicles were indistinguishable from one another. Specified as input, were:

- i) The number of intersections
- ii) The timing plan for each intersection
(a maximum of three phases).
- iii) The offset times
- iv) The distances between the intersections
- v) Required turning movements
- vi) The mean and standard deviation
of the (assumed normal) speed distribution on each link
- vii) Whether overtaking is allowed (the choice is between, effectively, an infinitely wide road where all vehicles may overtake, or a single lane road where none may overtake).

The output consisted mainly of average vehicle delay at various points in the system. The model was tested against a length of the Cromwell Road in the London area Traffic Control experiment area (ref. 1.48), since the Road Research Laboratory had collected field data for this location. At the preliminary stage of the investigation reported in the paper, two investigations had been carried out

- i) Variation of delay with signal timing
- ii) Variation of delay with the standard deviations of the speed distributions.

Agreement with observed field data was close, although the simulation tended to over estimate observed delays. The speed of the simulation produced a time advantage of the order of 10 : 1, but it varied with the complexity of the system being simulated. The authors say that

'generally speaking, the accuracy of the simulation is proportional to the square root of the length of the run'

although it is not clear whether this result has been observed by using this model only, or applies to simulation techniques in general.

1.3.6 Open Road Models

TAKATA (1965, ref. 1.49), working in Japan, developed a model to simulate two-way traffic on a level section of two-lane road. An infinitely long road was simulated by moving the vehicles around in two circles, one clockwise, and the other anticlockwise. By using a constant number of vehicles, but varying the circumference of the circles, different concentrations of vehicles could be simulated in each lane. The desired, or free, speed of each vehicle was found by random sampling from a normal distribution of variable mean and standard deviation, and, initially, headways were fixed by random sampling from a variable negative exponential distribution. Vehicles were allowed to travel at

their free speed until their time separation from the vehicle in front became lower than a threshold value T_m . The model was then examined to see if a passing opportunity existed by calculating the time required for a passing manoeuvre from the vehicle's speed at the time threshold, the speed of the vehicle in front and the known acceleration potential of a Japanese 1500 cc. car. If no such opportunity existed, the vehicle was forced to slow according to the following rule:

$$r_i = V_i - (V_i - v_{i-1}) \times \frac{\log S_i - \log (V_i \cdot T_m)}{\log d_i - \log (V_i \cdot T_m)}$$

where r_i is speed of ith car
 V_i is speed of ith car at threshold headway
 S_i is spacing of ith car
 d_i is following distance of ith car (the difference between S_i and d_i is not clear from the translation)
 v_{i-1} is speed of car in front.

The model was used to simulate the effects of restricted sight distances, speed limits, volume distributions and no-passing zones and, when run on UNIVAC - 1107 and IBM 7090 computers, produced a computer time/simulated time ratio of approximately 1 : 4.

WARNSHUIS (1967, ref. 1.50) used a similar model to simulate a similar situation with minor variations. He simulated a two-lane two-way road. The number of cars in each lane and the track length were variable, as was the desired speed of each car. At each iteration each car was moved as many feet as its speed in mile/h, so each scan corresponded to an advance in time of 0.682 s. Platoons or 'caravans' of cars were maintained at the speed of the leading vehicle and at a spacing corresponding to recommended driving practice in California -

one car length (constant at 20 ft.) for each 10 mile/h in speed. The author appreciated that in fact shock waves are observed to occur (ref. 1.51), but pointed out that at the concentrations he intended to simulate, platoons would be widely spaced and short, and therefore the shock wave effect would not be catastrophic. Acceleration and deceleration potentials were fixed at 4 mile/h/s for each car, and passing times were calculated on this basis. Various restrictions were imposed, such as the fact that an overtaking vehicle was only allowed to overtake one vehicle at a time, and that the second vehicle in the platoon made the overtaking manoeuvre before the third. Two speed distributions were used, one with a predominance of higher speeds and another with a predominance of lower speeds, and the number and length of platoons per mile of road were investigated at different concentrations. The program was written in FORTRAN V1 for an IBM 7090 computer, and the program simulated traffic at real time - no time advantage was obtained.

1.4 CONCLUSIONS

Examination of the work reported in section 1.3 enables three main conclusions to be drawn:

- i) Simulation backed up with accurate field data may be applied as a method of traffic analysis with confidence.
- ii) The method offers some advantages over other methods of traffic analysis.
- iii) As computing hardware and software has developed there has been a conspicuous shift in emphasis from the restrictions imposed by the computing operations to the restrictions imposed by the understanding of traffic operations, (e.g. cf. TAKATA (ref. 1.49) v. GERLOUGH (ref. 1.27)).

It is shown in Chapters 2 and 3 of this work that these three conclusions have been further substantiated by the application of simulation to the problems of right-turning traffic at traffic signals, and weaving traffic.

CHAPTER 1 : REFERENCES

- 1.1 HARLING, J., Simulation Techniques in Operations Research, Opns. Res. Jour., Nov-Dec. 1958.
- 1.2 WARDROP, J.G., The Traffic Capacity of Weaving Sections of Roundabouts, Proc. Opns. Res. Int. Conf., 1957.
- 1.3 HARTLEY, M.G., & D.H. GREEN, Study of Intersection Problems by Simulation on a Special Purpose Computer, Traff. Engng. & Control, 7 (3), Jul. 1965, 219-244, 229.
- 1.4 GREEN, D.H., Simulation of Merging Traffic Streams at an Uncontrolled Intersection, Dept. Elect. Engng., Univ. Manchester Inst. Sc. & Tech., 1965 (unpublished).
- 1.5 GREEN, D.H., Some Properties of Cross Merging Vehicles at Fixed Time Traffic Signals, Dept. Elect. Engng., Univ. Manchester Inst. Sc. & Tech., 1965 (unpublished).
- 1.6 HARTLEY, M.G., & S. SALEEB, Simulation & Study of Traffic Behaviour at Roundabouts, Dept. Elect. Engng., Univ. Manchester Inst. Sc. & Tech., 1965, (unpublished).
- 1.7 SALEEB, S., & M.G. HARTLEY, Simulation of Traffic Behaviour through a Linked-Pair of Intersections, Transpn. Res., 2 (1), Mar. 1968, 51-61.
- 1.8 HARTLEY, M.G., Modelling Techniques for Traffic Studies, Ph.D. Thesis, Dept. Elect. Engng., Univ. Manchester Inst. Sc. & Tech., Jan. 1968.

- 1.9 GREEN, D.H., M.G. HARTLEY & E.T. POWNER,
Research at the Manchester Institute of Science
& Technology, Area Control of Traffic, Proc.
Instn. Civil Engrs. Symp., London, Feb. 1967,
89-96, 107-114.
- 1.10 TANNER, J.C., A Theoretical Analysis of Delays at an
Uncontrolled Intersection, Biometrika, 49,
1962, 163-170.
- 1.11 MILLER, A.J., Analysis of Bunching in Rural Two-Lane
Traffic, Opns. Res., 11, 1963, 236-247.
- 1.12 LITTLE, J.D.C., Approximate Expected Delays for Several
Manoeuvres by a Driver in Poisson Traffic,
Opns. Res., 9, 1961, 39-52.
- 1.13 NEWELL, G.F., Queues for Fixed-Cycle Traffic Light,
Ann. Math. Statist., 31, 1960, 589-597.
- 1.14 HAWKES, A.G., Queueing for Gaps in Traffic, Biometrika,
52, 1965, 1-6.
- 1.15 DARROCH, J.N., On the Traffic Light Queue, Ann. Math.
Statist., 35, 1964, 380-388.
- 1.16 KELL, J.H., Results of Computer Simulation Studies as
Related to Traffic Signal Operation, 33rd
Annual Meeting Inst. Traff. Engrs., Toronto,
Aug. 1963.
- 1.17 CONSTANTINE, T., Simulation by Electronic Digital
Computer Traff. Engng. & Control, 5 (12),
Apr. 1964, 706-709.
- 1.18 ENGLISH ELECTRIC - LEO - MARCONI COMPUTERS Ltd.,
KDF9 Algol Programming, Publication No. 1002
mm (R) 1000565, Kidsgrove.

- 1.19 Revised Report on the Algorithmic Language ALGOL 60,
The Computer Journal, 5 (4), Jan. 1963.
- 1.20 MARKOWITZ, H.M., B. HAUSNER & H.W. KARR,
Simsript - A Simulation Programming Language,
Prentice-Hall Inc., New Jersey, 1963.
- 1.21 WATJEN, W.D., Computer Simulation of Traffic Behaviour
Through Three Signals, Traff. Engng. & Control,
6 (10), Feb, 1965, 623-626.
- 1.22 PARSLOW, R.D. Algol Simulator, Nat. Physics Lab., 1965.
- 1.23 DICK, A.C., Research at Newcastle upon Tyne University,
Area Control of Road Traffic, Proc. Instn. Civ.
Engrs. Symp., London, 1967, 97-106.
- 1.24 TOCHER, K.D., The Art of Simulation, English Universities
Press, London, 1963.
- 1.25 BEHRENZ, D.G., Algorithm 133, Comm. A.C.M., 5 (11),
Nov. 1962, 553.
- 1.26 MATHEWSON, J.H., D.L. TRAUTMAN & D.L. GERLOUGH,
Study of Traffic Flow by Simulation, Proc.
Highw. Res. Bd., 34, 1955, 522-530.
- 1.27 GERLOUGH, D.L. Simulation of Freeway Traffic by Electronic
Digital Computer, Proc. Highw. Res. Bd.,
35, 1956, 543-547.
- 1.28 GOODE, H.N., C.H. POLLMAR & J.B. WRIGHT, The
Use of a Digital Computer to Model a Signalised
Intersection, Proc. Highw. Res. Bd., 35, 1956,
548-557.

- 1.29 HILLIER, J.A., P.D. WHITING & J.G. WARDROP,
The Automatic Delay Computer, DSIR Road
Res. Lab. Res. Note No. RN/2291/JAH.PDW
JGW., Aug. 1954, (unpub.).
- 1.30 WEBSTER, F.V., Traffic Signal Settings, DSIR Road
Res. Lab. Road Res. Tech. Paper No. 39,
H.M.S.O. (London), 1958, 27-29.
- 1.31 BENSON, J.C., A Programme to Simulate on a Pegasus
II computer the behaviour of traffic at a single
intersection controlled by vehicle actuated signals,
DSIR Road Res. Lab. Lab. Note No. LN/182/
JCB, Sep. 1962, (unpub.).
- 1.32 FRANCIS, J.G.F. & R.S. LOTT, A Simulation Program
for Linked Traffic Signals, Proc. 2nd. Int. Symp.
Theory of Road Traffic Flow, London, 1963,
OECD, Paris, 1965, 257.
- 1.33 SCRAGGS, D.A., Computer Simulation of an Uncontrolled
T-Junction, MOT Road Res. Lab. Rep. LR124,
Crowthorne, 1968.
- 1.34 WOHL, M., Simulation - Its Application to Traffic
Engineering, Part 1, Traff. Engng., 30 (11),
Aug. 1960, 13-17, 29, & Part 2, Traff. Engng.,
31 (1), Oct. 1960, 19-25, 56.
- 1.35 PERCHONOK, P.A., & S.L. LEVY, Application of
Digital Simulation Techniques to Freeway On-Ramp
Traffic Operations, Proc. Highw. Res. Bd., 39,
1960, 506-523.
- 1.36 DAWSON, R.F., & H.L. MICHAEL, Analysis of On-Ramp
Capacities by Monte Carlo Simulation, Highw.
Res. Rec. No. 118, 1965, 1-20.

- 1.37 KELL, J.H., Analysing Vehicular Delay at Intersections through Simulation, 41st Ann. Meeting Highw. Res. Bd., Wash. D.C., Jan. 1962.
- 1.38 KELL, J.H., Intersection Delay obtained by Simulating Traffic on a Computer, 42nd Ann. Meeting Highw. Res. Bd., Wash. D.C., Jan. 1963.
- 1.39 GERLOUGH, D.L., & F.A. WAGNER, Improved Criteria for Traffic Signals at Individual Intersections, Planning Research Corporation, Los Angeles, Dec. 1965 (unpublished). *published NCHRP Rept No. 3, 32*
- 1.40 GERLOUGH, D.L., & F.A. WAGNER, Simulation of Traffic in a Large Network of Signalised Intersections, Proc. 2nd Int. Symp. Theory of Traffic Flow, London, 1963, 249-252.
- 1.41 GERLOUGH, D.L., Simulation as a Tool in Traffic Control System Evaluation, in HORTON, T.R. (Ed.), Traffic Control Theory & Instrumentation, Plenum Press, New York, 1965, 71-82.
- 1.42 FRANCIS, J.G.F., & R.S. LOTT, A Simulation Program for Linked Traffic Signals Proc. 2nd Int. Symp. Theory of Traffic Flow, London, 1963, 251-259.
- 1.43 DSIR ROAD RESEARCH LABORATORY, Research on Road Traffic, HMSO, London, 1965.
- 1.44 ASHTON, W.D., The Theory of Road Traffic Flow, Methuen, London, 1966.
- 1.45 GRIMSDALE, R.L., R.W. MATHERS & F.H. SUMBER, An Investigation of Computer-Controlled Traffic Signals by Simulation, Proc. Instn. Civ. Engrs., 25, Jun. 1963, 183-191.

- 1.46 WATJEN, W.D., Computer Simulation of Traffic Behaviour through Three Signals, *Traff. Engng. & Control*, 6(10), Feb. 1965, 623-626.
- 1.47 CRAFT, M.J., & J.L. SMITH, Road Traffic Simulation, *Plessey Comm. J.*, 1(3), 1967, 114-121.
- 1.48 COBBE, B.M., Questions & Answers on West London Traffic Scheme, *Traff. Engng. & Control*, 7(9), Jan. 1966, 562-565.
- 1.49 TAKATA, H., Applications of Computer Simulation Techniques to Road Traffic Analysis, *Trans. Japan Soc. Civ. Engrs.*, 124, Dec. 1965, 28-41, translated & summarised in Civil Engineering in Japan, 1966, *Jap. Soc. Civ. Engrs.* 119-121.
- 1.50 WARNSHUIS, P., Simulation of Two Way Traffic on an Isolated Two-Lane Road, *Transpn. Res.*, 1 (1), May, 1967, 75-83.
- 1.51 LIGHTHILL, M.J., & G.B. WHITHAM, On Kinematic Waves II, A Theory of Traffic Flow on Long Crowded Roads, *Proc. Roy. Soc., Series A*, 229, May 55, London, 317-345.

CHAPTER 2 : TRAFFIC SIGNAL SIMULATION

2.1 THE PROBLEM

2.1.1 The Right Turn Manoeuvre

A major problem in the design of any intersection is the conflict between right turning traffic and the oncoming stream. A lightly trafficked intersection presents no problem, the occasional right turning vehicle being left to filter between vehicles in the oncoming, or opposing, stream. At heavily trafficked traffic signal controlled intersections, however, right turning vehicles cause considerable interference with the straight ahead traffic whilst awaiting an opportunity to move through a gap in the opposing stream. The usual method of describing this interference effect is to express each right-turning vehicle in terms of a number of straight ahead vehicles, e.g. 'one right-turning vehicle = $1\frac{3}{4}$ straight ahead vehicles' (ref. 2.1). The difficulty is, however, that this ratio will not be constant, but will vary with traffic conditions: the effect of a right turning vehicle over and above that of a straight ahead vehicle on the stream behind it will obviously vary between little greater than zero when the opposing volume is very small, to very large when the opposing volume is high. (The effect of a right-turning vehicle over and above that of a straight ahead vehicle will never be zero because the vehicle must slow down in order to make the right turn manoeuvre, thereby delaying the passage of subsequent vehicles.) The major influence on traffic signal design in this country is the Ministry of Transport Road Research Laboratory at Crowthorne, and over the past few years they have made various recommendations about this problem.

2.1.2 Road Research Laboratory Recommendations

WEBSTER (1958, ref. 2.2) investigated saturation flows in London at several sites, and found the effect of right turning vehicles to be that illustrated by fig. 2.1. (The reader is referred to ref. 2.3, Appendix 1, for definitions of generally accepted terms such as 'saturation flow'.)

Average conditions were defined to be 10% right turning traffic, and 25% commercial vehicles, and saturation flows under other conditions expressed relative to these average conditions, hence the term 'relative saturation flow' as the ordinate in fig. 2.1. Whether this diagram forms the basis of the values of 'right-turning vehicle factor' quoted in the references listed below is not made clear in any of the literature. The overall gradient of the line (i.e. from 0 - 40% right turning traffic) is -0.30, between 0 and 20% right turning traffic -0.60, and the gradient of the tangent at 'average' conditions (10% right turning traffic) is -0.75. This last figure implies that a 1% increase in the proportion of right turning vehicles produces a 0.75% decrease in the saturation flow at a turning proportion of 10%. This does not necessarily correspond to a right turning vehicle factor of 1.75, however, as may be seen from the following example:-

Suppose the approach volume = 1,000 veh/h,
and saturation flow at 10%
right turns = 3,000 veh/h.

The gradient of the tangent to the curve on fig. 2.1 at 10% right turns is -0.75. Therefore, for a small increase of 1% in the proportion of right turning vehicles, the decrease in relative saturation flow is 0.75%, assuming the gradient of the tangent to be constant over the range 10 - 11% of right turning vehicles. Therefore the relative saturation flow at 11% right turning vehicles is $100\% - 0.75\% = 99.25\%$. For the values assumed above, this corresponds to an actual saturation flow of 99.25% of 3,000 = 2,977.5 veh/h - a decrease of 22.5 veh/h. This decrease is produced by a 1% increase in the proportion of right turning vehicles, which is 1% of 1,000 = 10 veh/h. Therefore the effect of a single right turning vehicle is $(22.5 - 10)/10 = 1.25$. It may be concluded that the effect of a single right turning vehicle will therefore depend, not only on the gradient of the line shown in fig. 2.1, but also on the ratio flow/saturation flow at the particular intersection arm. This fact seems to have been ignored in the later

literature, however.

CHARLESWORTH et al. (1958, ref. 2.4) give a figure of 1.6, also noting that the effect of right turning vehicles in Glasgow was less than that in London, and tentatively suggesting that this was owing to differences in driver behaviour in the two cities. A figure of 1.75 is quoted by WEBSTER et al. (1962, ref. 2.5) and by WEBSTER (1958, ref. 2.6), but with the cautionary note that it may tend to underestimate the effect because

' cases where right turners were given special phases or where they frequently blocked the intersection were omitted.'

The authors also recommend that a special phase be provided at intersections where more than five right turning vehicles/cycle are expected. In ref. 2.7, 1.75 is again used, but mention is made of the difficulty of measuring saturation flows over the whole approach under heavy right turning conditions, and it is stated that it may be advisable to treat right turning and straight ahead lanes separately, but that

' No simple rule can be given to cover all cases. They have to be dealt with on their merits, bearing in mind the purpose for which the saturation flow results are to be used.'

Reference (2.8) recommends that 1.75 only be used with light right turning movements and that a separate lane be provided if the movement is heavy. If no separate lane is provided

' and vehicles waiting to turn are sufficiently numerous to obstruct the straight ahead flow, the saturation flow of the remaining vehicles may be estimated from the reduced approach width; a reduction of 7 ft. may suffice for a turning stream of cars and light vans, but one of 9 ft. may be needed where there is a high proportion of heavy vehicles.' (P.69)

Similar sentiments are expressed in ref. 2.9 (paras. 329 and 330).

It will be noted that none of the above works make mention of the effect of the volume of the opposing stream, but WEBSTER and COBBE (1966, ref. 2.3) and WEBSTER (1967, ref. 2.10) made good this discrepancy as follows:-

The effect of right turning vehicles at traffic signals is said to be three-fold.

- i) The right turning vehicles are delayed therefore causing delay to those vehicles behind them.
- ii) Their presence in the right-hand lane inhibits use of that lane by straight ahead vehicles because of the risk of being delayed.
- iii) Those right-turning vehicles which remain in the intersection at the end of the green period take a certain time to discharge and may delay the start of the cross phase.

The authors then state that effects (i) and (ii) may be allowed for

'by assuming that on average each right-turning vehicle is equivalent to $1\frac{3}{4}$ straight-ahead vehicles.'

Then follows a description of a method to calculate the number of right-turning vehicles that may be expected to filter through the opposing stream during each green period under differing opposing flow conditions using average volume and the minimum acceptable gap to right turning vehicles. By comparing this number with the average number of vehicles expected to arrive during each cycle, the number of vehicles/cycle that apply effect (iii) may be calculated and the signal timings adjusted to suit by providing some special phase enabling them to clear.

2.1.3 Other Work on the Right-Turning Problem

ARCHER et. al. (1963, ref. 2.11), working at Imperial College, London, investigated six arms of five intersections in the London area using time-lapse photography. Assuming a straight line relationship between left and right-turning vehicle factors, and by comparing observed saturation flows with those predicted from stopline width by Webster's formula (ref. 2.6), the lines

$$La + RB = K$$

were plotted, where

- L = Percentage of left turning p.c.u.'s observed for a given arm,
- R = Percentage of right turning p.c.u.'s,
- a = 'Capacity ratio' of one left turning p.c.u.
- B = 'Capacity ratio' of one right turning p.c.u.
- K = Reduction in capacity (value predicted from stopline width - observed value),

for each arm. The intersection of five of the lines (one line gave non-sensical results because of the peculiar layout of the junction) gave values of 1.25 for a and 1.75 for B. No mention was made, however, of the volumes encountered in the opposing stream by the right turning traffic.

American practice is similar to that in this country. Ref. 2.12 (p.83) points out that

'Under adverse conditions, the effect of turning

movements may be sufficiently great to reduce the practical capacity of an intersection on a two-lane road or street by as much as 50%.

The manual goes on to say that:

'..... each 1% of the total traffic turning right (left in U.K.) reduced the capacity flow $\frac{1}{2}$ % and that each 1% of the total traffic turning left (right in U.K.) reduced the capacity flow 1%.'

The more recent edition of the manual (ref. 2.13) takes a slightly different approach similar to that of WEBSTER (ref. 2.2) by tabulating adjustment factors for various conditions including approach widths, and parking conditions against the percentage of turning vehicles (table 6.5, ref. 2.13), using unity for 'average' conditions, i.e. 10% left (right, in U.K.) turns. These tabulated results have been combined to form the diagram shown in fig. 2.2 for the 'no parking on approach' condition, and they apply only to right turns on a two lane approach in a two way street, with no special facilities for right turning vehicles such as a special phase or exclusive lane. (The results are similar when parking is allowed, but 5 ft. is added to the width limitations on the curves.) The following characteristics of right turning vehicles are noted in the text (p.122):

- 'i) The effect per vehicle on approach capacity is less if two successive vehicles turn left (right in U.K.) than if single vehicles turn at more widely spaced intervals. It follows that the larger the number of turning vehicles the less the effect per vehicle.
- ii) The effect of left (right) turning vehicles is related to the number of opposing vehicles on two-way streets.'

and, further on,

- 'iii) A vehicle waiting to make a left (right) turn causes a greater relative reduction in capacity on a narrow street than on a wider street

With reference to characteristic (ii), however, there is no mention of any precise relationship between the effect of right turners and the opposing flow.

It becomes apparent from the foregoing that a more exact knowledge of the relationship between the effect of right turning vehicles and the opposing flow would be useful to practising traffic engineers, and that if the relationship could be expressed in a more convenient form than that in ref. 2.3, so much the better. PRETTY (1966), working in Australia, appreciated this in his work described in ref. 2.14. He quotes an empirical formula developed by LEONG (1964, ref. 2.15) which states that

$$S_1 = 1700 - 11p_1$$

where S_1 = Saturation flow for one lane of traffic (veh/h.)

p_1 = Proportion of right turning vehicles as a percentage of total flow,

and says that three other factors should be taken into account, viz:

- i) The volume of the opposing flow, (q_o)
- ii) The percentage of right turners in the opposing flow, (p_1)
- iii) The volume of the flow being studied.

He investigated the effect of these three factors by the use of a simulation model on an IBM 1620 digital computer, modelling a four arm intersection with two approach lanes on each arm. A constant scanning interval was

chosen so that one vehicle was discharged from the queue at each scan. The arrival times of the vehicles were obtained from a binomial sequence, a fixed minimum acceptable gap was assumed, and the model simulated either fixed-time or a simple form of vehicle actuation. Using regression analysis based upon 51 combinations of p_1 and q_0 he found that, for fixed time signals,

$$S_1 = 1780 - 0.000568 p_1 q_1 q_0 - 0.00777 p_1^2 q_0 + 0.0000333 p_1^2 q_1 q_0$$

where S_1 = Saturation flow,

and $S_1 = 1780 - 0.117 p_1 q_0$

for vehicle-actuated signals.

No details are given of the degree of fit of the simulated results to the above equations.

GORDON et. al. (1966, ref. 2.16) tackled the same problem but used a combination of analytical and simulation techniques. The signal cycle was divided into three effective parts, making the simplifying assumptions that the queue was discharged completely during every green period, and that the signals were fixed-time. The parts were

- i) The effective red period
- ii) The time period during which the queue of vehicles opposing the right turn movement is discharging from the intersection.
- iii) The time period after the queue has discharged and before the change of signal indication.

The mean and variance of the queue discharge period was found using probability theory, and hence, since the cycle and green times are fixed, the mean and variance of the period after queue discharge. The absence of published data on gap acceptance distributions of right turning vehicles

at traffic signals forced the authors to adopt a fixed 'critical gap', and difficulties encountered in describing the distribution of available gaps theoretically forced them to simulation techniques as a method of estimating the number of vehicles able to turn right during each cycle. A suitable model was designed for use on an IBM 1620 computer, and approximately 22 hours of real time simulated. The results gave

$$S_R = 1200 \times_Q \frac{\lambda s - q}{s - q} + \frac{3600 k}{C}$$

- where
- S_R = Right turn capacity
 - \times_Q = Probability of being able to make a right turn (derived from the simulation, and shown on fig. 2.3).
 - λ = Ratio g/c
 - g = Effective green time
 - C = Cycle time
 - q = Flow
 - s = Saturation flow
 - k = Average number of right turns made during the all red and amber periods.

(λ, g, c, q , and s all apply to the opposing approach)

The authors then adapted the equations to suit practical conditions, giving

$$\begin{aligned} S_{\text{prac.}} &= 0.7 S_R \\ &= 840 \times_Q \cdot \frac{\lambda s - q}{s - q} + \frac{2520}{C} \cdot k \end{aligned}$$

This equation was tested against field data and appeared to give conservative results, but they make mention of the difficulties of obtaining sufficient field data in order to test the model fully, and suggest that

it be tested against a full simulation model. As a counter to suggestions that it might have been better to use a full simulation model in the first place, the authors point out that the analytical approach helped in the formation of the equations above – equations which would have been difficult to deduce from the results of a simulation model.

2.1.4 A Solution

Unfortunately, the work of PRETTY and GORDON was unknown to the author at the start of this work, but the problem was apparent. Simulation seemed an ideal tool for analysis, the only other alternative being an extremely ambitious field study requiring laborious data collection and analysis. The aim was to construct a model which was as flexible as possible so that it could be applied to a wide range of intersections whilst bearing in mind that flexibility usually means a substantial increase in programming time and complexity. Since any simulation model must be verified, and also since the model requires certain data as input, a site was chosen to act as a model for the simulation. The fact that the simulation was modelled on a particular intersection, however, does not preclude its use in other traffic situations. This will be made clearer in sections 2.3 and 2.4.

2.2 DATA COLLECTION AND ANALYSIS

2.2.1 The Test Site

A test site was required for three reasons:

- i) To act as a preliminary model for the simulation
- ii) To collect realistic estimates of traffic behaviour
- iii) To verify the simulation.

The site chosen was the junction of Clayton Road and the Great North Road (A1), north of Barras Bridge, Newcastle upon Tyne. A sketch plan of the intersection is shown in fig. 2.4. This particular site was chosen primarily because of its layout: the fact that no right turn was possible for southbound traffic meant that no difficulties of conflicting right turn movements were possible, thereby simplifying the collection of field data. This in no way detracts from the general usefulness of the simulation, however, since vehicles rarely make right turns round each other (offside - offside), but usually make 'non-hooking' turns (nearside - nearside). (It is possible that the lack of conflicting right turners for the eastbound traffic enabled them to accept shorter gaps because of better visibility, but this is not known.) Other reasons for choosing this particular site were:

- i) Absence of parked vehicles
- ii) Absence of pedestrian interference
(they were provided with a special phase).
- iii) Good visibility for the manoeuvring vehicles
- iv) Proximity to the Department of Civil Engineering.

A major disadvantage was the absence of any tall buildings in the vicinity which might have provided a camera vantage point (data was collected

using time-lapse photography).

The A1 at this point is a four-lane single-carriageway road, 40 ft. wide with good sighting distances, no gradients, and a 30 mile/h. speed limit, which changes to 40 mile/h. just north of the intersection. Also, just north of the intersection is a bus stop for north bound buses, but it was rarely used and had little, if any, effect on the north bound saturation flow. The left hand lane of the south bound approach has since been designated an experimental 'bus and left turning vehicles only' lane, but the field data was collected before this experiment began. Clayton Road is a narrow (24 ft.) two-lane single-carriageway road through a residential area, linking the A1 with Jesmond Road which is a spine road in a large area of dense housing. Consequently a constant supply of right turners was available, during the evening peak period, of shoppers and workers returning to their homes from the city. The signal controller was a three-phase vehicle-actuated controller (the pedestrian phase being available on demand from a push button), but the north bound flows from the city were high enough to extend the green to a maximum for most of the time making the operation of the signals effectively fixed time. Both the northbound and southbound approaches were clearly divided into two lanes up to a 20 ft. wide stop line. The right hand lane of the northbound approach was marked with a right turn arrow, but by no means did this inhibit its use by straight ahead vehicles.

2.2.2 Gap-Acceptance

The ability of a right turning vehicle to filter through an opposing traffic stream depends upon two factors:

- i) The shortest gap in the opposing stream that the particular vehicle/driver will accept in that particular situation (minimum acceptable gap), and
- ii) The frequency of occurrence of a

gap in the opposing stream equal to or greater than this minimum acceptable gap.

Item (i) depends upon many factors which may be grouped under three main headings:

- i) Driver characteristics
- ii) Vehicle characteristics
- iii) Intersection characteristics.

Driver characteristics might include such factors as age, sex, temper, trip purpose, (business or pleasure); vehicle characteristics; power/weight ratio, size and type, condition, whilst intersection characteristics might include sight distances, gradients, radii of turns, and weather conditions.

Obviously, therefore, for any particular intersection a description of minimum acceptable gaps must be in the form of a distribution rather than a single value.

2.2.2.1 Collection of Gap-Acceptance Data

The gap acceptance data was collected using time-lapse cinematography. (Details of the equipment are given in Chapter 4.) The absence of tall buildings around the site was a difficulty, but an adequate field of view was attainable from the north-east corner of the intersection (see fig. 2.4). The camera was mounted on a tripod about 5 ft. high, fitted with a 10 mm. wide-angle lens and photographs taken in a south-westerly direction of the traffic turning right from the A1 into Clayton Road. 580 ft. of film was exposed, details of which are given in Table 2.1.

At this stage of the work, only four camera speeds were available: 1 frame/s triggered by the mechanical timer, and 8, 16 or 24 frames/s obtained by continuous running of the camera motor through the camera gear box. The accuracy and performance of the equipment is discussed more fully in Chapter 4, but suffice to say that the continuous running

speeds of the camera were not constant by any means, and could only be considered as a nominal 8, 16 or 24 frames/s. The actual running speeds depended upon a variety of factors such as the particular camera being used, the state of charge of the battery pack and the amount of film on the take-up spool in the magazine. The mechanical timer was unreliable, being rather temperature sensitive, but was more accurate than the camera motor. It was decided that 8 frames/s or faster would be wasteful of film, and so the mechanical timer was used to give 1 frame/s. This meant that gaps could only be measured to the nearest second, and also that a check was needed during filming of the speed of the mechanical timer. This check was attempted by holding a stop watch in front of the camera at intervals so as to compare elapsed time from the start of filming with the number of frames exposed. During the filming of film no. A1/CR1 the light was not strong enough to allow a sufficiently large depth of field (ref. 2.17) and the watch was either out of focus or too distant to be read accurately. The light was strong enough in the second film (A1/CR 2), and fig. 2.5 shows the discrepancy between the number of frames exposed and the elapsed time. Although the governor on the motor had been set as accurately as possible before leaving the laboratory, it may be seen from fig. 2.5 that the error in the timer varied between -3% and +5%. Over the whole film, however, the error was 0.5%. These errors would obviously be of some consequence when observing traffic over a long period of time - say a classified count - but since gaps in this study were only measured to the nearest second, they were judged to be unimportant. They were sufficiently large, however, to lead to the development of more accurate equipment for future work.

Films A1/CR 1 and A1/CR 2 were exposed continuously during the evening peak periods. After analysis of these films it was decided that more information was required about gaps large enough to be accepted by two vehicles, and film was only exposed whilst two or more right-turning vehicles waited at the stopline during the green period.

2.2.2.2 Gaps and Lags

Two situations arise:

- i) A gap in the opposing stream is accepted by a vehicle (vehicle C, fig. 2.6) waiting at the stop-line.

This manoeuvre is hereafter known as 'gap-acceptance', and the time interval between the passage of vehicle A past the point where C is waiting and the passage of vehicle B is known as the accepted 'gap'.

- ii) Vehicle C (fig. 2.7) arrives at the stop-line when vehicle A has passed, (hence vehicle A does not influence the manoeuvre in any way) and moves across the path of vehicle B.

This is known as 'lag-acceptance', and the time interval between the arrival of vehicle C at the stop-line and the passage of vehicle B past the stop-line is known as the 'time-lag', or more commonly, 'lag'.

An acceptable lag and acceptable gap to any particular vehicle might be supposed to be different because

- i) In lag acceptance, the vehicle will incur no starting delay because it is already moving at the decision point (for the purposes of this discussion the decision point will be assumed to be vehicle C's stop-line), and
- ii) In the gap acceptance manoeuvre vehicle C must observe a minimum headway behind vehicle A before moving off, a factor of no account in lag acceptance.

Initially, therefore, one would expect an acceptable lag to be shorter

than an acceptable gap, and shorter by an amount which is some function of the driver's reaction time, acceleration time, and safe following headway. The data was analysed with this distinction in mind.

2.2.2.3 Analysis of Photographic Data

As at this stage the only reasonably accurate camera speed available was 1 frame/s, it was decided to group gap sizes into groups of one second. It would have been possible to interpolate between whole numbers of seconds, but no attempt was made to do so since the data was merely required as input to the program, a method was available to enable a smooth curve to be drawn through the resulting histogram, and GREEN (1965, ref. 218) has provided evidence that

'Provided the variation is not large, any of the usual types of random gap acceptance distributions may be approximated by an equivalent step distribution.'

The analysis method was a simple procedure, and best explained by reference to a series of photographs taken at the test site (fig.2.8). (These photographs were taken by a 35mm. camera, as the quality of reproduction from the 16mm. movie camera is poor. They were exposed at approximately one second intervals from the same place as the movie.)

Photograph 1: Vehicle A is waiting at the stopline to turn right. The signals on vehicle A's phase are at green, vehicle C is a straight ahead vehicle, and vehicle B is an opposing vehicle forming the front of the gap that vehicle A accepts.

Photograph 2: Vehicle A judges the gap to be large enough and moves through the opposing stream.

Photograph 3: Vehicle A continues to manoeuvre. Vehicles D and E are moving up to the stop-line.

Photograph 4: Vehicle D judges the time lag between his arrival at the stop-line and arrival of the next vehicle

in the opposing stream to be safe, and moves into the opposing stream.

Photograph 5: Vehicle D continues to manoeuvre. Vehicle E moves across the stop-line into the opposing stream.

Photograph 6: Vehicle E continues to turn.

Photograph 7: The gap closes with the arrival of vehicle F.

Therefore we may conclude from the evidence on photographs 1 - 7 that:

- i) Vehicle A accepted a gap of 6 seconds,
- ii) Vehicle D accepted a lag of 4 seconds,
- iii) Vehicle E accepted a lag of 2 seconds,

assuming the interval between the photographs to be approximately one second.

The drivers turning right fall into several categories: if there is no queue, and a driver arrives at the stop-line travelling at a high (relatively speaking) speed, say, 15 mile/h, he either accepts the lag in the opposing stream or rejects it by stopping at the stop-line. These two situations are easy to distinguish. If the driver stops he waits for an acceptable gap, rejecting those which he judges to be too short. Here again, these two situations are easy to distinguish. If there is a queue at the stop-line however, some difficulty is experienced in deciding precisely where and when the second and further drivers in the queue make their decisions to accept or reject gaps or lags. Suppose the queue leader moves off, and while the second driver moves up to a position where he can accept or reject the remaining lag, the lag closes. Did this second driver reject the remaining lag available to him, or was he not in a position to avail himself of this lag? If the latter be the case,

could he have moved his vehicle to the stop-line in a shorter time had he decided to accept the lag? It was found impossible to answer these questions from the photographic evidence, and so a different approach was adopted. By investigating the gaps accepted by the first two vehicles in the queue and comparing this distribution with that for one vehicle, an attempt was made to reach some conclusions about the amount of time taken for the first vehicle to clear the intersection and the amount of lag left available to the second vehicle. This approach produced spurious results which are discussed in 2.2.2.4, but this is the reason that film A1/CR.3 was only exposed when two consecutive vehicles that had indicated a desire to turn right were waiting together at the stop-line.

2.2.2.4 Analysis Methods

It is reasonable to suppose that there is a minimum size of gap or lag that a particular driver will accept, and also that the size of this gap or lag will be different for different drivers. The simulation requires knowledge of the distribution of minimum acceptable gaps or lags, and so the field data must be analysed to give this distribution. It has been suggested (ref. 2.21) that the ideal way to observe gap acceptance behaviour would be to present each driver with a series of gaps that gradually increased in size until he accepted one. If the increment in gap size with each successive gap were small enough, one could then assume that the first gap the driver accepted would be his minimum acceptable gap. Unfortunately, this kind of approach is impossible unless large laboratory facilities are available, with the attendant disadvantage of unreality when compared with actual traffic conditions. When observing gap acceptance behaviour in the field, one must use the data available: in the case of a driver turning right into a side road, the driver may be presented with four gaps of various sizes, the last of which he accepts. It may be construed from this evidence that the first three gaps were smaller than his minimum acceptable gap, and that the last was larger, but in this particular driver's case, the information is no more precise than that. By repeating similar observations for a sample of drivers

one can obtain the total number of rejections and the total number of acceptances for gaps of any particular size. By calculating the proportion of the presented gaps that are accepted, plotting these proportions against gap size, and drawing a smooth curve through the points, it is possible to estimate the probability of a gap of a particular size being accepted provided that there is a vehicle waiting. This is not necessarily the same, however, as the cumulative distribution of minimum acceptable gaps amongst the sample of drivers, the reason being that although a driver may accept but one gap, he may reject several. This means that the greater the preponderance of smaller gaps, the more rejected gaps that will be observed for a constant number of accepted gaps (that is, where the queue of turning vehicles is stable). This distinction between the two distributions has been appreciated by some authors and not by others.

Gap and lag acceptance has been studied in connection with traffic manoeuvring at

- i) Uncontrolled T junctions
- ii) Intersections of major and minor streets
- iii) Entrances to weaving sections
- iv) On ramps.

GREENSHIELDS (1947, ref. 2.20) was the first in the field with a study of gap acceptance at at-grade cross roads using time lapse photography. He made an attempt to describe the resulting distribution in terms of one parameter, as other authors have done, and defined the lag of a size accepted by more than 50% of the drivers as the 'accepted average-minimum time gap', or 'minimum-acceptable time gap'.

GOURLAY (1948, ref. 2.22) and STRICKLAND (1948, ref. 2.23), both using photographic techniques developed by Greenshields (op. cit.) continued investigations into gap acceptance by studying merging at on-ramps

and at roundabouts respectively. Merging vehicles were divided into three speed groups, and Greenshields 'minimum-acceptable time gap' used to describe the resulting distributions.

RAFF (1950, ref. 2.19) was the first to make the distinction between gap and lag, and was also the first to appreciate the danger of introducing a bias by using more than one rejected gap or lag in the analysis: he used only the lag, noting whether it was accepted or rejected, and rejected all other data for that particular driver. The parameter he employed to describe the resulting distribution he termed 'critical lag (L)', defined as that 'size lag which has the property that the number of accepted lags shorter than L is the same as the number of rejected lags longer than L'. This was found by plotting both the number of rejected lags for each lag size and the number of accepted lags for each lag size against lag size on the same diagram, the intersection of the two curves giving the critical lag (see fig. 2.9). He investigated side street vehicles crossing the main stream at four different intersections in New Haven, Conn., using a moving pen recorder, and found that the critical lag varied between 4.6 - 5.9s, depending upon site conditions.

BISSELL (1960, ref. 2.24) investigated gap and lag acceptance by left and right turning and straight vehicles at two intersections in California using a pen recorder similar to that used by Reff. By plotting the observed data on logarithmic probability paper and fitting parallel straight lines by inspection, he concluded that there was no significant difference between minimum acceptable lag and minimum acceptable gap distributions. He reported a mean combined lag and gap acceptance of 5.8s.

BLUNDEN et al. (1962, ref. 2.21) observed driver behaviour in Sydney in an attempt to fix accurately the shape of the gap acceptance distribution, the authors criticising earlier work for a lack of concentration on this aspect. They appreciated the problem of the driver rejecting more than one gap, but accepting only one, and two methods were proposed to overcome this situation:

- i) Study of all the cars that are confronted by a particular sized gap and noting the number that accept or reject, thereby finding the proportion of drivers that will accept a gap of that size. The observations are repeated for a full range of gap sizes.
- ii) By noting the size of all gaps passing waiting drivers and whether they are accepted or rejected. The number of rejections are then reduced proportionally for each gap size so that the total number of rejections is equal to the total number of acceptances.

Fisher used method (i), but it is not clear from the text whether one particular driver was tested against one gap only, or several. If the former, then the resulting distribution would give the cumulative distribution of acceptance gaps amongst the drivers - the desired result. If the latter, the bias would still be present. Clissold used method (ii), but it is difficult to see how this device would correct the bias - in the author's opinion it merely disguises it.

SOLBERG et al. (1966, ref. 2.25) refined Bissel's technique by fitting a straight line to a logarithmic transformation of the data by a technique known as probit analysis (ref. 2.26, 2.27, 2.28).

Probit analysis is a method of processing quantal response data in order that significant conclusions may be made about the population from which the sample is taken. Quantal response data, or 'all-or-nothing' data is obtained from a system where a subject is exposed to a stimulus and reacts in one way or another, e.g.

<u>Subjects</u>	<u>Stimuli</u>	<u>Responses</u>
Rats	Poison doses	Death or survival
Sacks	Impacts	Breakage or no breakage
Patients	Drug doses	Recovery or no recovery
Drivers	Gaps	Acceptance or rejection

The response is always of a kind where there is no gradation between the two extremes of response – the subject either reacts or does not react. Assumptions usually made by the method when applied to gap acceptance are

- i) The minimum stimuli, or the logarithm of the minimum stimuli that produce positive responses are normally distributed throughout the population
- ii) For any particular stimulus the probability of positive response is binomially distributed through the sample.

The method is fully explained in Appendix 1, but consists basically of a transformation of the proportions of drivers accepting gaps against gap size into a form amenable to a linear regression technique.

Solberg (op. cit.) used a cine camera running at 8 frames/s to collect information at two sites in Lafayette and two in Indianapolis. Vehicles entering a main street from a side street controlled by a stop sign were observed, and a distinction was made between gaps and lags: the difference between mean lag and mean gap at the intersections in Lafayette was found to be insignificant, as was that for Indianapolis. A distinction was also made between left, right and through manoeuvres, and the differences were in some cases significant, and not in others. The authors did not, apparently, test the improvement to the fit of the probit line obtained by using a logarithmic transformation of the gap size, although pointing out

that earlier work had indicated that the transformation was desirable. Also, it is not made clear in the paper whether a driver rejecting the first gap was tested against ensuing gaps or not. They analysed their data by the methods employed by Raff and Bissell, thus providing an interesting comparison between the different techniques. The results are reproduced as Table 2.2.

WAGNER (1966, ref. 2.29) concluded from work at one intersection at Michigan that not only was there a significant difference in the gap and lag distributions, but that the mean of the gap acceptance distribution was less than the mean of the lag acceptance distribution. He used a multipen event recorder and seems to have tested drivers that rejected the first gap more than once, since he states (p. 72)

'The decisions and reactions of 1203 separate side street vehicles, giving rise to a total of 5179 separate lag or gap acceptance decisions, were extracted from the records.'

This being the case, the surprising result of the mean gap being less than the mean lag is even less understandable. The results were analysed by plotting the results on log-probability paper and fitting a curve by eye.

RORBECH (1966, ref. 2.30) used Raff's critical lag method of analysis for traffic at three intersections in Denmark in an experiment designed to investigate the change in critical lag with turning direction and speed of the main road traffic. The results of the turning movement investigation were inconclusive, but he found that the critical lag increased with increase in speed of the main road traffic.

ASHWORTH, et al. (1966, ref. 2.31) working at Liverpool discovered that there was no significant difference between gaps and lags, or the behaviour of turning traffic and straight through traffic, or between heavy and light vehicles. They make mention of the fact that since all rejected gaps were observed and analysed, the resulting composite gap acceptance distribution did

' not indicate the percentage of drivers prepared to accept a given gap size, but rather the percentage of gaps accepted.'

DREW (1967, ref. 2.32), observing merging behaviour at entrance ramps to freeways in Texas, observed the longest rejected gap by any one driver, together with the gap he finally accepted. He plotted the results on log-probability paper (c.f. Bissell, ref. 2.24) and used Raff's method to define the critical gap. He then proposed that the critical gap distribution could be described by consideration of the range of gap values between the longest gap a driver rejected and the gap he accepted. Assuming that the driver's critical gap lay within this range, he then plotted the observed frequencies of critical gaps as a histogram by dividing the number of times the critical gap range included a certain gap interval by the total number of gap intervals. He found that although a normal curve fitted the observed frequency diagram reasonably well, it assigned a finite probability to negative critical gaps, and that a Pearson Type III distribution was more satisfactory.

Other work in the field includes that by WORRAL et al. (1967, ref. 2.33) on gap acceptance by more than one vehicle at freeway entrance ramps, HARMELINK (1967, ref. 2.34) working on turning lane capacities in Canada, BUHR (1968, ref. 2.35) on freeway merging, SALTER (1968, ref. 2.36) at priority intersections in Bradford, together with work at the Road Research Laboratory by CHARLESWORTH, et al. (1960, ref. 2.37) and BENBOW (1962, ref. 2.38), and work on gap acceptance at roundabouts by YOUNG (1965, ref. 2.39) and TING (1968, ref. 2.40).

ASHWORTH (1968, ref. 2.41), commenting further on his remarks in an earlier paper (ref. 2.31) about the bias introduced by testing a driver more than once when he rejected a gap, developed a method for eliminating the bias when using gap acceptance data in simulation studies. By assuming random arrivals in the main stream and that minimum acceptance gaps were distributed normally amongst merging drivers, he showed that

'the gap acceptance curve giving the probability of a gap of length t being accepted is the original (i.e. true) cumulative normal curve displaced by an amount $s^2 q$ from its former position'

where s is the standard deviation of the distribution of minimum acceptance gaps and q is the major road flow. He goes on to clarify the above:

'Thus if the gap acceptance criteria are such that 50% of drivers are prepared to accept a gap greater than or equal to $5.5s$ and the standard deviation of the distribution is $2s$, then with a main stream volume of 900 veh/h the gap size having a 50% chance of acceptance, is $5.5 + 4 (900/3600) = 6.5s$, and in order to simulate this acceptance distribution, it would be necessary to use a mean of $5.5s$ (not 6.5) in the simulation model.'

He verified the above by simulation studies carried out with main stream volumes from 300 to 1500 veh/h , the gap acceptance curves showing successive displacements to the right. One of the curves (main stream volume = 1500 veh/h) is shown as the right hand curve on fig. 2.10. This curve shows the probability of gaps of various sizes being accepted (i.e. the distribution OBSERVED when taking each rejected gap into account), together with the actual distribution of minimum acceptable gaps (the left hand curve) used as input to the simulation, with mean $5.5s$ and standard deviation $2s$. (The curves are not shown in ref. 2.41, but were used by Ashworth in the development of his method.)

From all the foregoing, some points emerge:

- i) The cumulative distribution of the minimum acceptable gaps of drivers,

and the probability curve of a gap being accepted are not coincident.

- ii) The cumulative distribution of the minimum acceptable lags of drivers, and the probability curve of a lag being accepted are coincident.
- iii) There may or may not be a statistically significant difference between minimum lag and minimum gap distributions.
- iv) The turning direction of the manoeuvring vehicle appears to affect the distributions.
- v) The vehicle type has no significant effect on the distribution.
- vi) The minimum lag and distributions may be distributed normally, log normally, or as a Pearsen Type III distribution.
- vii) No data is available for vehicles turning right at traffic signals.

The problem, therefore, remains - how to obtain the distribution of minimum acceptable gaps. Consideration of Ashworth's work suggests one method, i.e. by observing all rejected gaps and the main stream flow, processing the information by probit analysis, and subtracting $s^2 q$ from the mean of the observed distribution. This approach presupposes that:

- i) The distribution of minimum acceptable gaps is normal,
- ii) The distribution of gaps in the main stream is exponential,

and a more direct approach is desirable. Consideration of the lag

distribution suggests another approach: each driver is tested against one lag only. Applying this approach to gap acceptance, when the vehicle may reject many gaps, leads to the question of which gap to test the vehicle against. Drew (ref. 2.32) used the longest gap, but in this work it was decided to test the vehicle against the first gap presented to it, in order to preserve a close parallel to toxicological work in biology for which the technique of probit analysis was designed. In a typical application of probit analysis a rat might be given a dose of poison. If the rat survives, it obviously cannot be tested again with a larger dose, because it will have been affected by the non-lethal dose. The same reasoning would apply to a test to the strength of sacks - the first impact may not break the sack, but might damage it, nullifying its usefulness as a further test specimen. This effect, of course, cannot be applied too closely to traffic work because a driver who has rejected a gap too small for him will presumably not lower his threshold of gap acceptance appreciably until he has rejected many gaps, although this admittedly is pure conjecture. In any case, if this effect were judged to be significant, it would necessitate selecting a minimum acceptable gap from a different distribution every time the vehicle rejected a gap within the simulation model.

Another objection to testing the vehicles against the first gap only is that, in order to be in a gap acceptance situation, the vehicle must have already rejected a lag. If it be assumed that

- i) The lag and gap acceptance distributions are different, and
- ii) A vehicle with a relatively long minimum acceptable lag will require a long minimum acceptable gap,

then there is still a source of bias in the method. However, it was felt that this source of bias must be ignored owing to the lack of reasonable alternatives.

2.2.2.5 Analysis and Conclusions

The gap and lag acceptance data was obtained from the films as described in Section 2.2.2.1, and is shown in Tables 2.3 and 2.4, and as histograms on figs. 2.11 and 2.12. Table 2.3 and fig. 2.11 show the data for lag acceptance, and Table 2.4 and fig. 2.12 that for gap acceptance based upon the first gap presented to the waiting vehicle, no other gaps being considered. The smooth curves shown on the figures are the probit lines fitted to the untransformed data. Since the lines gave a satisfactory fit, no logarithmic transformation of the gap size was attempted. The calculations involved in fitting the probit line to the lag acceptance data are shown in Appendix 11, and those for the gap acceptance in Appendix 111. For comparison, the gap acceptance data including all the rejected gaps were analysed and Ashworth's correction applied. The data is shown in Table 2.5 and on fig. 2.13, and the derivation of the probit line and the correction shown in Appendix IV. The results of the investigations are summarised in Table 2.6. The curves were compared with each other by using the Variance Ratio Method and the Students t-Test Method for the means.

i) Gap Acceptance

The curve obtained by applying Ashworths correction to the curve obtained by including all the rejected gaps was compared with that obtained by using the first gap only.

$$\text{Variances:} \quad F = \frac{1.5225^2}{1.3330^2} = 1.304 \text{ (436, 435df.)}$$

The difference in the variances is significant at the 5% level.

$$\begin{aligned} \text{Means:} \quad \text{Variance } (\bar{x}_1 - \bar{x}_2) &= \frac{1.5225^2}{437} + \frac{1.3330^2}{436} \\ &= 0.008969 \end{aligned}$$

therefore

$$t_{\infty} = \frac{5.5450 - 5.1352}{\sqrt{0.008969}} = 4.327$$

The difference between the means is significant at the 0.1% level, i.e. these two curves are by no means the same but, according to Ashworth's theoretical approach, they should be identical. The difference that exists presumably arises because Ashworth's method assumes random arrivals in the major road flow, whereas at this particular site arrivals were controlled by the traffic signals. Also the fit of the probit line for all the rejected gaps was not good, and therefore it is difficult to draw any conclusions for this particular test of Ashworth's method. The curve obtained by analysing the first gaps only was used in the simulation model.

ii) Gap and Lag Acceptance

The gap acceptance curve obtained by analysing the first gap only was compared with that obtained for lag acceptance.

$$\text{Variances: } F = \frac{1.3330^2}{0.9855^2} = 1.830 \text{ (436, 154 df.)}$$

The difference in the variances is significant at the 5% level.

$$\begin{aligned} \text{Means: } \text{Variance } (\bar{x}_1 - \bar{x}_2) &= \frac{1.3330^2}{436} + \frac{0.9855^2}{154} \\ &= 0.01038 \end{aligned}$$

$$\text{therefore } t_{\infty} = \frac{5.1352 - 4.1208}{\sqrt{0.01038}} = 9.9548$$

The difference in the means is significant at the 0.1% level, i.e. the two distributions are totally different, as expected. Therefore, a distinction

was made in the model between gap acceptance behaviour by stopped vehicles and lag acceptance behaviour by moving vehicles.

2.2.3 Arrival Distributions

It is necessary in most traffic simulation models to describe the arrival pattern of vehicles at one or more points in the model. This could be achieved by reading in arrival headways that have been observed, but a more compact and flexible method is to describe the arrival headways by means of a distribution and to use random sampling when the next arrival gap is required by the model.

ADAMS (1936, ref. 2.42) was among the first authors in the field to suggest that vehicular traffic could be described mathematically as a random series. He said that light to medium traffic (i.e. under volumes of 1000 veh/h, a rate of flow apparently rarely obtained in 1936) was distributed at random in both time and distance (except whilst under some control) and could therefore be described by the Poisson Distribution. The Poisson Distribution is a particular case of the Binomial Distribution, (ref. 2.43) and states that

$$P(x) = \frac{m^x e^{-m}}{x!}$$

where $P(x)$ = Probability of x vehicles arriving in a time interval t

m = Mean number of vehicles arriving in a time interval t

e = Base of Napierian logarithms.

The distribution of headways may then be described by the Negative Exponential Distribution which is derived from the Poisson distribution (ref. 2.43, p.25).

Let $m = \lambda t$

where λ = Number of vehicles arriving per second
 t = Time interval.

Then the probability of no vehicles arriving in a time interval t is

$$\begin{aligned} P(O) &= \frac{m^0 e^{-m}}{0!} \\ &= e^{-m} \\ P(O) &= e^{-\lambda t} \end{aligned}$$

$P(O)$ is the probability that no vehicles will arrive in a time interval t . This is the same as the probability that the next gap is at least as long as t , i.e.,

$$P(g \geq t) = e^{-\lambda t}$$

This distribution is known as the Negative Exponential Distribution. It is open to the objection that in single file traffic at high volumes the vehicles are no longer distributed at random but are influenced by the vehicle in front. This led to the development of the Shifted Negative Exponential Distribution (ref. 2.44), where the probability of a gap less than a certain minimum headway is zero. Expressed in its cumulative form,

$$P(g < t) = 1 - e^{-(t - T) / (\lambda - T)}$$

where T = minimum headway.

SCHUHL (1955, ref. 2.45) developed a distribution named the Composite Exponential Distribution (ref. 2.44) for use on two lane roads where a certain proportion, a , of the vehicles were 'constrained', i.e. unable to overtake, whilst the remaining proportion were free to overtake and thus exhibit zero headways.

$$P(g < t) = (1 - a) (1 - e^{-t\lambda_1}) + a (1 - e^{-(t - T)\lambda_2})$$

where λ_1 = Average rate of flow of the
unconstrained vehicles,
 λ_2 = Average rate of flow of the
constrained vehicles.

This distribution gives a very good fit to observed data reported in ref. 2.45, but its use is difficult in simulation, owing to the difficulty of deciding upon a value for a , and hence λ_1 and λ_2 , for varying volumes of traffic.

BUCKLEY (1962, ref. 2.46), in a paper summarising work in the field of headway distributions, has listed some objections to the use of the exponential distribution except at low volumes, but he concedes that in multi-lane facilities the fit is adequate for most practical purposes. He also quotes NEWELL (1956, 2.47)

' delays are somewhat insensitive to the form of the statistical distribution of the headways of the arriving traffic streams and that, to a reasonable order of accuracy, the assumption of random arrivals is probably satisfactory for this problem.' (i.e., traffic signals).

An investigation into the arrival pattern of vehicles at the test site was carried out. Vehicles on the northbound approach were investigated (see fig. 2.4), but some difficulty was encountered in deciding precisely when a vehicle had arrived when the signal aspect was red, or when queueing was taking place because of the differing deceleration rates employed. A position about $\frac{1}{4}$ mile south of the intersection was therefore chosen as an investigation site, which was far enough away from the end of an average queue for the vehicles' speed to be unaffected, and yet was close enough to be representative of arrivals at the intersection itself. The vehicle headways were timed and recorded on a Rustrak Model 92

4-channel Event Recorder. The apparatus, which is described in detail in Chapter 4, is basically a device for recording 'on-off' data. A reel of paper is drawn at constant speed under four pens. When activated by an electrical signal, the pens are displaced sideways a small amount and when the signal terminates, the pens return to their former position leaving a straight line trace with rectangular 'blips'. Each pen was wired to a particular push button enabling four different sequences of events to be recorded simultaneously, the whole apparatus being powered by rechargeable dry cells.

In this case - arrival distributions - only two channels were used. One channel was used to record the passage of vehicles between the observer and a lamp standard perpendicularly opposite on the far side of the road, and another channel to provide a calibration check for the paper speed. Every minute measured on a stopwatch was recorded as a blip on the chart on this calibration channel. A total of 901 gaps were observed during the evening peak hour of 6th May, 1965 in 48 minutes - equivalent to an hourly volume of 1126 veh/h - the relevant data being given in Table 2.7 and figs. 2.14 and 2.15. The negative exponential, and shifted (or truncated) negative exponential curves have also been calculated for a flow of 1126 veh/h, and are shown in Table 2.7 and figs. 2.14 and 2.15. These curves are both significantly different from the observed distribution at the 0.1% level, as determined by the Chi-Squared Test, the greatest differences occurring in the short headways. The choice of a one-second minimum headway for the shifted curve was entirely arbitrary, but inspection of fig. 2.15 indicates that major improvements in the fit would be unlikely with different values. Despite the obvious discrepancies between the actual and theoretical distributions, however, the shifted negative exponential distribution was used because

- i) Newell has shown that the form of the arrival distribution has relatively little effect upon delay (ref. 2.47)

- ii) Although the fit is statistically unacceptable, inspection shows the two distributions to be similar over most of the range of gap sizes.
- iii) The distribution is extremely convenient to handle mathematically making the generation of gaps fast and simple.
- iv) The shifted negative exponential curve has the added advantage that no vehicle can arrive at a headway less than a specified minimum. Although this may be inaccurate from the traffic point of view, it means that no difficulties are encountered in the model of more than one vehicle arriving on the same approach at one particular scanning time, making construction of the model much simpler. This advantage is only realised, of course, if the scanning interval is made less than or equal to the minimum headway.

2.3 THE TRAFFIC MODEL

2.3.1 In General

The model is intended to represent one arm of an intersection similar in layout to the test site shown in fig. 2.4. The fact that there is no western arm does not affect the model in any way, since only the north-south axis is considered. No physical distances are represented in any way - vehicles arrive at the intersection, wait, and discharge from it, and there is no mechanism in the model for the deceleration of arriving vehicles and the acceleration of leaving vehicles. The model makes no distinction between types of vehicles - all are considered to be identical cars - and can only model a two lane approach. A constant scanning interval is employed, but the length of the scanning interval is at the discretion of the user, and must be read in as data at the beginning of a run. A 'run' is denoted by an identification number, also read in at the beginning of each run, and consists of a simulation of one particular set of traffic conditions. It is impossible to change the traffic conditions before the end of the run, but a print out of results may be obtained at any time during the run. The times for these print outs are at the discretion of the user and must be specified in the input data (a maximum of 11 intermediate print outs is enforced. A twelfth print out time specifies the time for conclusion of the run). Since all the stores, such as queues, start empty, the model must be run for a settling down period before useful results can be obtained. This aspect of the model is discussed more fully in section 2.5. A flow diagram for one run is shown in fig. 2.16, and the layout of the intersection shown in fig. 2.17.

2.3.2 Vehicle Arrivals and Queueing

Decisions as to whether a vehicle has arrived on either arm (fig. 2.16, box F2, C4, A7 etc.) and decisions about the size of the available gap in the opposing stream are made by inspecting two 'gap-stores', one for each arm. If, at any particular scan interval, either of these stores is equal to or less than zero, the next gap in the stream is generated by using a random sampling method and the cumulative shifted negative

exponential distribution.

From section 2.2.3,

$$P(g < t) = 1 - e^{-(t - T) / (\lambda - T)}$$

where $P(g < t)$ = Probability of a gap less than t

T = Minimum gap

λ = Average gap.

Solving this equation for t (the next gap),

$$t = (\lambda - T) (-\log (1 - P)) + T$$

Substituting a random fraction, r ,

for $(1 - P)$,

$$t = (\lambda - T) (-\log r) + T$$

$$t = T - (\log r) (\lambda - T). \quad (\text{ref. 2.44})$$

Therefore, by substituting a random fraction in the above equation, the next gap may be generated and added into the appropriate gap store. (It will be appreciated, from Section 1.2.4, that the random number generator requires a starting number. This starting number is read in at the beginning of the run - box B1.) By subtracting one scan interval from each gap store at each scan (box B2) the position in time of the next vehicle is kept continuously: when either of the stores reaches zero or less, a vehicle is said to have arrived and a new gap is generated. This method suffers from the limitation that only gaps longer than the scan interval can be handled - hence the use of the shifted negative exponential distribution.

The model also requires knowledge of whether a vehicle arriving on the approach road is in the left hand or right hand lane, and, if the right hand lane, whether it is a vehicle intending to turn right (boxes H2 and H11). A random fraction is therefore generated and by comparing this random fraction with the proportion of right turning vehicles and the

proportion of vehicles which are in the right hand lane but do not intend turning right, the vehicle's lane position and turning movement is fixed.

If the signals are at red, or a queue is present the recently arrived vehicle joins the queue appropriate to its lane. For programming reasons a limit of 1000 vehicles is enforced for the right hand queue, and the program terminates if this limit is reached. No such limit exists for the left hand queue.

2.3.3 Signals

Boxes G3, H3, A11, E11, G11, H12, G13, H13, and C16 all require knowledge of the state of the signal controller. A fixed time controller is simulated since the model was designed for use under heavy traffic conditions, and a vehicle actuated controller runs to maximum and becomes effectively fixed time under such conditions. The program requires knowledge of the cycle time, red time, amber time, green time and lost time for the approach, and calculates from this information the effective green time for the approach from the equation

$$g_{\text{eff.}} = g + a - l \quad (\text{ref. 2.3})$$

where $g_{\text{eff.}}$ = Effective green time

g = Actual green time

a = Amber time

l = Lost time.

The effective red time is then found by subtracting the effective green time from the cycle time.

A facility for simulating an early cut-off or late start for the opposing approach is available, and information is required by the program as to whether such a facility is required, and if so, whether it is to be a late start or early cut-off, and the length of time/cycle required for its

operation.

It was observed that, under heavy traffic conditions, right turning vehicles at the front of the queue in the right hand lane would move off immediately on receipt of a green signal, turning in front of the opposing queue before it began to clear. It was also observed that vehicles waiting to turn right would do so at the beginning of the red period, manoeuvring against the red signal and in front of the opposing traffic which was slowing to a halt. Accordingly, this traffic behaviour is simulated in the model so that accurate calibration tests can be carried out when actual observed data is being used. At the test intersection it was found that, on average, if the first two vehicles in the right hand lane queue were right turning, at the start of the red, they would move off in front of the decelerating opposing traffic (boxes A11, B11, C10, D10, E10, F10), and that, if the first vehicle in the right hand lane queue at the start of the green was right turning, the vehicle would move off in front of the opposing queue on 37% of such occasions (boxes C16, D16, E16, F16, and G16). This facility may be omitted by the user by indicating on the input data tape whether it is required: if it is required, the proportion of right turning vehicles that moves off in front of the opposing queue must be given.

2.3.4 Queue Clearance and Saturation Flows

Vehicles in the left hand lane queue suffer no interference from other traffic, and so they are free to move off during the green period. At each scan interval a portion of the queue is subtracted from it, and this portion is equal to the number of vehicles that would cross the stop line during one scan interval. The saturation flow rate for the left hand lane is therefore required by the program. Suppose that the saturation flow rate for the left hand lane is 1600 veh/h, and that the scan interval is 1.5s, then

$$1600/3600 \times 1.5 \text{ veh} = 0.667 \text{ veh}$$

would be subtracted from the left hand lane queue at each scan, provided that some vehicles or fractions of a vehicle were present (boxes H15 and G15). A check is also kept within the program of the number of vehicles

actually generated: two stores are used – one for straight ahead vehicles and another for right turning vehicles (F15, C9).

Clearance of the right hand lane queue is more complicated. First of all the first vehicle in the queue is examined to find out whether it is a straight ahead vehicle or a right turning vehicle (e.g. F3). If it is a straight ahead vehicle, the appropriate 'manoeuvre store' is consulted to see whether the preceding vehicle has had time to clear (e.g. H7). If so, the vehicle is subtracted from the right hand lane queue and a 'manoeuvring time' added into the manoeuvre store. This manoeuvring time will depend upon the straight ahead saturation flow in the right hand lane, e.g. if the saturation flow is 1600 veh/h, the time taken for one vehicle to clear the stopline will be $3600/1600s = 2.25s$. One scan interval is subtracted from the two manoeuvre stores at each scan (D2).

If the first vehicle in the queue is a right turning vehicle the state of the opposing queue is examined (e.g. E4). If the opposing queue has cleared, and the previous vehicle is no longer manoeuvring (A4), a minimum acceptable gap is selected by random sampling from the appropriate gap acceptance distribution and compared with the available gap in the opposing stream. If the minimum acceptable gap is smaller than the available gap, the vehicle is subtracted from the right hand lane queue, and its manoeuvring time added into the appropriate manoeuvre store. If not, the vehicle remains at the head of the queue, retaining the same minimum acceptable gap, and waits for the next gap in the opposing stream.

2.3.5 Saturation Flow of Right Turning Vehicles

During the clearance of a queue of right turning vehicles, it is necessary to know how much of the available gap is used by the first vehicle in the queue, in order that the minimum acceptable gap for the second vehicle and the remaining available gap may be compared. An investigation into the gap acceptance behaviour of groups of two vehicles was made, the reasoning being that the difference in the means for the gap acceptance curve for two vehicles and for one vehicle would give the average man-

oeuvring time for the first right turning vehicle. Film number A1/CR 3 (Table 2.1) was exposed specifically to collect information for this purpose, and the data obtained, together with that from A1/CR 1 and 2 is shown in Table 2.8. A group of two vehicles was deemed to have accepted a gap when both vehicles accepted it, and to have rejected it when the first vehicle only accepted it. Fig. 2.18 shows the data as a histogram and the transformed probit line as fitted in Appendix V. Since there would only be one rejection of the type defined above for each pair, no question of bias arose.

As may be seen from Appendix V, the cumulative normal curve fitted to the gap acceptance data for pairs of vehicles has a mean of 6.1357s and a standard deviation of 1.4560s, the fit, as tested by the Chi Squared Test, being significant at the 5% level. Thus, from Table 2.6, the difference in the mean minimum acceptable gap for a stopped vehicle and a pair of vehicles is $6.1357 - 5.1352 = 1.0005\text{s}$. Were this difference to be used as a manoeuvring time for a right turning vehicle, however, it would lead to saturation flows in the right turning lane of $3600/1.0005$; or approximately 3600 veh/h. Obviously, therefore, since the observed saturation flow in this particular lane is approximately 1600 veh/h, the reasoning must be wrong, and another estimation must be made. (The field data and analysis have been recorded in this work for the interest of other workers in the field.)

Knowledge of the turning rate of a queue of right turning vehicles would provide information about the clearance time of one particular right turning vehicle, but no field observations were possible at the test site because of the mixture of turning and straight ahead vehicles, and the discontinuous nature of the turning movement.

WEBSTER (1964, ref. 2.48) in some work on this topic at the Road Research Laboratory has shown that for a single line of turning traffic, the practical time interval or headway for a line of cars is

$$(2.0 + 10/r) \text{ s/pcu,}$$

where r = turning radius in feet.

Measurement of the turning radius of vehicles at the test site from a scale plan indicates that the approximate value of r in this case is 28 ft. Substitution in the above equation gives an average headway for turning vehicles of 2.357s/pcu. (It should be noted that substitution of infinity for r in the above equation gives a value of 2.0s/pcu for the straight ahead case. This corresponds to a value of 1800 veh/h/lane, which is higher than that at the test site. The value of 2.357s may therefore underestimate the turning headway.) Since the angle turned through at the site is not 90° as in the R.R.L. experiment, but 82°, a value of 2.3s was used in the simulation, rather than 2.4s. This value was added into the manoeuvre store for right turning vehicles.

A distinction is made in the model between the first vehicle in the queue and subsequent vehicles (e.g. B9). The distinction was drawn because it was suspected that queueing vehicles other than the first vehicle in the queue might exhibit different gap acceptance behaviour from the first vehicle. It was not possible to verify this suspicion because of the difficulty in deciding whether or not a queueing vehicle had rejected a gap. If the second vehicle in the queue rejects the remainder of the gap left by the first vehicle whilst crawling up to the stop line, two possibilities exist

- i) The gap is too small,
- ii) The gap would have been large enough had the vehicle been in a position to accept it, i.e. closer to the stop line.

Unfortunately, then, the question at present remains unanswered, but the distinction is still made in the flow diagram and the program, and minimum acceptance gaps are selected from the stopped vehicle acceptance distribution (fig. 2.12) for all queueing vehicles. When either a straight

ahead or a turning vehicle leaves the right hand lane queue, its manoeuvring time plus one scanning interval is added into a 'following' store (e.g. G7). As with the manoeuvre stores, one scanning interval is subtracted from the following store at each iteration (box E2), and therefore when the vehicle has cleared there will remain a value of one scanning interval within the store, for one iteration enabling the program to decide whether the next vehicle in the queue immediately follows the vehicle in front.

Two definitions of saturation flow have been employed - 'two lane' saturation flow, and 'single lane' saturation flow. The saturation flows are measured by observing the number of vehicles that cross the stop line under either of the saturated conditions and the time for which either of the conditions obtain. The two lane saturation flow condition exists when both the left hand and right hand lane queues are discharging, and the printed out rate includes compensation for the fact that a right turning vehicle requires longer to clear the intersection than a straight ahead vehicle. The single lane condition exists when there are queues in both lanes whether the right hand lane queue is discharging or not. The two lane condition is used primarily as a check that the program is working correctly, but the single lane condition is used to calculate the rating of right turning vehicles (R). R is derived from the equation

$$S = (X + Y \times R) / T$$

where S = Saturation flow of straight ahead vehicles over both lanes, as input to the program

X = Number of straight ahead vehicles simulated as crossing the stop line under single lane saturation flow conditions

Y = Number of turning vehicles simulated as for X

T = Time for which single lane saturation flow conditions obtain.

Hence

$$R = (S \times T - X) / Y$$

Saturation flows and their definitions will be discussed more fully in Section 2.7.2 where the results of the simulation are given. It will be noted that lost time is used in the calculation of the effective green time, and accordingly that the first vehicle in the queue is not treated as being different from subsequent vehicles in needing a longer clearance time.

2.3.6 Delays

The delay to vehicles queueing on the approach is calculated by summing the queues, multiplying by the scanning interval and adding the result into a 'delay' store (C2). The printout includes the total delay in vehicle seconds, the delay per arrived vehicle, the delay per discharged vehicle (the difference between these last two may be considerable when the approach is oversaturated). A delayed vehicle is defined as a vehicle which joins one of the approach queues.

2.4 THE PROGRAM

2.4.1 In General

The program was written to be used on an English Electric KDF9 installation with either the Whetstone or Kidsgrove compilers (see section 1.2.2), and is divisible into four main parts. The first declares the identifiers and procedures required by the program, and reads all the data for all the runs required, storing the data until required. The tape reader is then switched off so as to be available to another user when the machine is being used in its time-sharing mode. The second part is called at the beginning of each run, and extracts from the data store the data relevant to the particular run and assigns it to the appropriate identifiers, sets all other identifiers to their initial values, and prints out the data as read in on the line printer. The third part is the actual simulation and consists of a loop which is repeated at each scan. The fourth prints out the current value of the stores when required. The particular run may stop at this stage, or return for further simulation and intermediate print outs, as required. At the end of a run the program either stops or returns to the second part for the next run, as desired.

2.4.2 Identifiers

An 'identifier' is, in its Algol context, the name given to a store, and may consist of a letter followed by any combination of numbers and letters. Various restrictions affect the maximum length of identifiers, depending upon the compiler. The identifiers in the program are listed below in alphabetical order, together with the quantity held in the store to which they apply. An 'array' is an identifier which represents a group of stores, each particular store in the group being distinguished by a subscript or subscripts in square brackets after the identifier, or array, name, and all identifiers are described to the machine as being 'real' or 'integer', depending upon whether the stores are required to store real numbers or integers.

The identifiers used in the program are:

1. AHEAD : Manoeuvre store for vehicles moving straight on from the queue in the right hand lane.
2. Amber : Length of the amber period
3. ARRIVE : Gap store for the approach
4. ASPECT : A boolean value (assuming a value 'true' or 'false') depending upon whether the signals are at green (true) or red (false). This device is used merely to make the program easier to follow.
5. C : Lower limit for the random number generator.
6. Cheat 1 : The number of vehicles simulated to move off from the front of the queue just after the end of the green period.
7. Cheat 2 : The number of vehicles simulated to move off immediately following the beginning of the green period.
8. Cheet 1 : If this value is 1, the part of the program simulating the manoeuvre described in item 6 will be called.
9. Cheet 2 : As for item 8, except that item 7 will be simulated.
10. Cycle : The cycle length of the signal controller.
11. Cycletime : The current length of time since the start of red for this cycle.

12.	d	:	Upper limit for random number generator
13.	DELAY	:	Current total vehicle delay since start of run for the approach only
14.	DELVEH	:	Number of vehicles in the approach which have been delayed
15.	early	:	Length of early cut-off for signal controller (zero if not required)
16.	effgreen	:	Effective green time deduced from input signal timings
17.	FILTER	:	Boolean value, true if a late start or early cut-off is required
18.	FOLLOW	:	Manoeuvre store to enable the program to deduce whether the current lead vehicle in the right hand lane queue is immediately following another
19.	GAP	:	Gap store for the opposing stream
20.	gm	:	Minimum acceptable lag for the vehicle currently arriving in the right hand lane of the approach
21.	green	:	Green time for the approach
22.	GREEN	:	Boolean value. Holds the value true, used in conjunction with item 4.
23.	gs	:	Minimum acceptable gap for vehicle currently at the front of the right hand lane queue
24.	head	:	Holds the position of the queue leader in the array 'Q' (see Section 2.4.3)
25.	i	:	Used as a counter in some computation routines

26.	k	:	Used as a counter to record the next print out time (used in conjunction with array 'thyme')
27.	late	:	Late start time (zero if not required)
28.	LHLANEQ	:	Number of vehicles in the left hand lane queue
29.	lostime	:	Lost time for the approach
30.	LTSASATI	:	Number of (left turning and) straight ahead vehicles discharged whilst both queues are discharging. ('Both lanes' saturation flow conditions.)
31.	LTSASAT2	:	Number of (left turning and) straight ahead vehicles discharged whilst the left hand lane queue is discharging and there are vehicles in the right hand lane queue, discharging or not. ('Single lane' saturation flow conditions.)
32.	LTSAVS	:	Number of (left turning and) straight ahead vehicles discharged under any condition
33.	maxlhq	:	Maximum number of vehicles appearing in the left hand lane queue so far in this particular run
34.	maxrhq	:	As above for right hand lane queue
35.	mingap	:	Minimum headway in approach and opposing approach arrival distributions
36.	MOVETURN	:	Manoeuvre store for right turning vehicles accepting a lag

37.	moving	:	Clearance time for a right turning vehicle accepting a lag
38.	N	:	Number of runs required
39.	OPPDELAY	:	Current total vehicle delay since the start of the run for the opposing arm
40.	p	:	Counter used in association with array 'thyme' to read in print out times
41.	pcu	:	The right turning vehicle rating to be assumed for the calculation of delay to be expected by the RRL method (ref. 2.6)
42.	Print	:	The number of print outs required during this particular run
43.	r	:	Used to hold the current random number
44.	red	:	Red time on the approach arm
45.	RED	:	Boolean value, holding the value 'false'. Used in conjunction with items 4 and 22
46.	REPEAT	:	Counter, holding the number of runs started since the beginning of computation
47.	RHLANEQ	:	Number of vehicles currently in right hand lane queue
48.	riteturn	:	Rating of right turning vehicles computed from saturation flow simulation
49.	rt	:	Proportion of vehicles in the approach turning right
50.	RTSATI	:	Number of vehicles turning right under 'both lane' saturation flow conditions (see item 30)

51.	RTSAT2	:	Number of vehicles turning right under 'single lane' saturation flow conditions
52.	RTUS	:	Number of vehicles turning right under any condition
53.	run	:	An identification number for the run
54.	rush	:	The proportion of first in line right turners that are prepared to turn in front of the opposing queue immediately after the start of green
55.	sa	:	The proportion of vehicles in the approach which are straight ahead vehicles but in the right hand lane
56.	sattime 1	:	The length of time for which 'both lane' saturation flow conditions obtain
57.	sattime 2	:	The length of time for which 'single lane' saturation flow conditions obtain
58.	sB	:	The straight ahead saturation flow over the whole width of the opposing stopline
59.	sLH	:	The straight ahead saturation flow for the left hand lane of the approach
60.	sRH	:	The straight ahead saturation flow for the right hand lane of the approach
61.	STOPTURN	:	Manoeuvre store for right turning vehicles accepting a gap
62.	stopped	:	Clearance time for a queueing right turning vehicle

63.	STREAMBQ	:	The number of vehicles queueing on the opposing approach
64.	t	:	Scanning interval
65.	TIME	:	Elapsed time since start of run
66.	VA	:	Hourly approach volume over both lanes
67.	VB	:	Hourly volume on opposing arm
68.	yo	:	Starting random number
69.	z0	:	Third parameter in random number specification (constant at zero)

Array identifiers are:-

1.	data	:	A two dimensional array storing the initial data read from the data tape until required
2.	Q	:	A one dimensional array storing the turning movements of vehicles in the right hand lane queue
3.	thyme	:	A one dimensional array storing the print out times for the run.

2.4.3 Procedures

A 'procedure' is a sub-routine of programming which may be called at any time simply by writing its name. Procedures used in this program are:

1. Random This procedure is a standard Algol procedure and is explained in Section 1.2.4.

2. Queue This procedure adds or subtracts vehicles from the queue in the right hand lane. The turning movements of vehicles in the right hand lane queue are stored in the array Q, and the turning movement for vehicle number x is stored in a store labelled Q x in the form of 1 for a right turning vehicle and 0 for a straight ahead vehicle. When a vehicle leaves the queue, one is subtracted from the quantity RHLANEQ, and one is added to the 'marker' denoted by the identifier, 'head' (see fig. 2.19). In fig. 2.19, for instance, if the first vehicle left the queue, 'head' would become equal to 68, and 'RHLANEQ' equal to 6. If a vehicle joined the queue, 'RHLANEQ' would become equal to 8, and Q 13 would become equal to 1 if the additional vehicle was a right turning vehicle, or 0, if straight ahead. Such a method of storing information is rather extravagant with computer storage space, since each store is used only for the small proportion of the simulation time that any one particular vehicle is in the right hand lane queue, and the array must be large enough to be able to provide space for every vehicle passing through the queue - maybe of the order of 5,000 vehicles in a ten hour long simulation. In order to overcome these two objections, a circular store is set up (see fig. 2.20), where the last element in the array is joined onto the first. The size of the store will depend upon the amount of information it is required to store at any one time - in this case 1,000 vehicles. (This is the reason for the run terminating when more than 1,000 vehicles are present in the right hand lane queue.) In this case, fig. 2.20 as vehicles depart from the head of the queue, the head marker 'head' becomes successively 998, 999, 1000, 1, 2, 3, 4 and 5.

3. Picklag and Pickgap These two procedures select a minimum acceptable lag and gap, respectively, from the distributions shown on figs. 2.11 and 2.12 by random sampling. The distributions are not followed exactly but by linear interpolation between the ordinates corresponding to integer values of the abscissae.

2.4.4. Text of Program

begin library A0,A6;
integer N;

open(20); open(30);
writetext(30,[[p]VSO13**s*1*sumner[c]traffic*
signal*simulation*****program*number*2.21
[c]]);
N:=read(20);

begin comment data tape details:

First, THE NUMBER OF RUNS REQUIRED, and then,
FOR EACH RUN:-

1. The run number (integer, number).
2. Number of print outs required (integer, number, and with a maximum value of 12), and then the time required for print outs (integer, number).
3. Scan interval (real, seconds).
4. The first random number (integer). (This number must be an odd, eleven digit number which is less than 34,359,738,368).
5. Cycle time (real, seconds).
6. Red time (real, seconds).
7. Amber time (real, seconds).
8. Green time (real, seconds).
9. Early cut-off time (real,seconds).
10. Late start time (real,seconds).
11. Lost time per phase (real, seconds).
12. Saturation flow in left hand approach lane (real, veh/hr eff green).
13. Saturation flow in right hand approach lane (as above).
14. Approach volume (real, veh/hr).
15. The proportion of vehicles in the approach which are right turning (real, ratio).
16. The proportion of vehicles which are in the right hand lane and straight ahead (real, ratio).
17. Saturation flow on opposing arm (real, veh/hr eff green).
18. The opposing volume (real, veh/h).
19. Time taken by a moving vehicle to clear the stopline (real, s).
20. Time taken by a stopped vehicle to clear the stopline (real, s).

21. Minimum headway in approach and opposing traffic (real, seconds).
 22. The right turning vehicle factor to be assumed in the RRL delay calculation (real, ratio).
 23. If right turning vehicles are required to move off just after the start of the green, in front of the opposing queue, this value should be 1.
 24. If vehicles are required to move off just after the end of green, this value should be 1.
 25. The proportion of first in line right turners that move off in front of the opposing traffic when the lights change to green (real, ratio).
- AND FINALLY, after all the data, -1000;

integer y0,z0,i,DELVEH,RHLANEQ,maxrhq,
 head,run,cheat1,cheat2,cheet1,
 cheet2,REPEAT,print,p,k,check;

integer array Q[1:1000],thyme[1:12];

real array data[1:N,1:37];

real GAP,DELAY,LHLANEQ,MOVETURN,gm,
 RTSAT1,RTSAT2,LTSASAT1,LTSASAT2,
 gs,sRH,AHEAD,LTSASVS,RTVS,FOLLOW,
 ARRIVE,c,d,VA,rt,red,amber,green,
 early,late,TIME,losttime,effgreen,
 cycle,STREAMBQ,sB,VB,sLH,t,r,
 STOPTURN,sa,sattime1,sattime2,
 riteturn,maxlhq,mingap,moving,
 stopped,rush,pcu,cycltime,
 OPPDELAY;

boolean RED,GREEN,ASPECT,FILTER;

real procedure random(a,b,x0);
value a,b,x0; real a,b; integer x0;
begin own integer x,m35,m36,m37;
 if x0 \neq 0 then


```

begin
    x:=x0;
    m35:= 34 359 738 368;
    m36:= 68 719 476 736;
    m37:=137 438 953 472;
end;
x:=5*x;
if x>m37 then x:=x-m37;
if x>m36 then x:=x-m36;
if x>m35 then x:=x-m35;
random:=x/m35*(b-a)+a
end random;

procedure queue(turn,s,error);
boolean s; integer turn; label error;
begin comment If vehicle is right turning,
turn = 1. If vehicle is left turning or
straight ahead, turn=0. If vehicle is
leaving the queue, s=false. If vehicle
is arriving, s = true;
if s then
begin integer next;
if RHLANEQ>999 then goto error;
next:=if (head+RHLANEQ-1)<1000
then head+RHLANEQ else head+
RHLANEQ-1000;
if next>1000 or next<1 then
begin
writetext(30,[head*=*]);
write(30,format([-ndddd]),
head);
writetext(30,[rhlaneq*=*]);
write(30,format([-ndddd]),
RHLANEQ);
write text(30,[at*time]);
write(30,format([ndddsddd]),
TIME)
end;
Q[next]:=turn;
RHLANEQ:=RHLANEQ+1;
if RHLANEQ>maxrhq then maxrhq:=
RHLANEQ;
end
else
begin

```

```

head:=if head=1000 then 1 else
  head+1;
RHLANEQ:=RHLANEQ-1;
if RHLANEQ<0 then
  begin
    writetext(30,[rhlaneq*=*]);
    write(30,format([-ndddd]),
      RHLANEQ);
    writetext(30,[at*time*]);
    write(30,format([ndddsdddc]),
      TIME)
  end
end;
end of queue;

real procedure pickgap;
begin switch number:=one,two,three,four,five,
  six,seven,eight,nine,
  ten;
  r:=random(c,d,z0);
  goto number[entier(10×r)+1];
one: if r<0.05 then pickgap:=1.5+(2.5-1.5)×
  10×r×2 else pickgap:=2.5+(3.4-2.5)×
  10×(r-0.05)×2;
  goto out;

two: pickgap:=3.4+(4.0-3.4)×10×(r-0.10);
  goto out;

three: pickgap:=4.0+(4.4-4.0)×10×(r-0.20);
  goto out;

four: pickgap:=4.4+(4.8-4.4)×10×(r-0.30);
  goto out;

five: pickgap:=4.8+(5.1-4.8)×10×(r-0.40);
  goto out;

six: pickgap:=5.1+(5.5-5.1)×10×(r-0.50);
  goto out;

seven: pickgap:=5.5+(5.8-5.5)×10×(r-0.60);
  goto out;

eight: pickgap:=5.8+(6.3-5.8)×10×(r-0.70);

```



```

        goto out;
nine: pickgap:=6.3+(6.9-6.3)×10×(r-0.80);
      goto out;
ten:  if r<0.95 then pickgap:=6.9+(7.5-6.9)×
      10×(r-0.90)×2 else pickgap:=7.5+(9.0-
      7.5)×10×(r-0.95)×2;
out:
end   of pickgap;

```

```

real procedure picklag;
begin switch roman:= I,II,III,IV,V,VI,VII,
                     VIII,IX,X;
      r:=random(c,d,z0);
      goto roman[entier(10×r)+1];
I:    if r<0.05 then picklag:=1.5+(2.5-1.5)×
      r×10×2 else picklag:=2.5+(2.9-2.5)×10
      ×2×(r-0.05);
      goto exit;
II:   picklag:=2.9+(3.3-2.9)×10×(r-0.10);
      goto exit;
III:  picklag:=3.3+(3.7-3.3)×10×(r-0.20);
      goto exit;
IV:   picklag:=3.7+(3.9-3.7)×10×(r-0.30);
      goto exit;
V:    picklag:=3.9+(4.1-3.9)×10×(r-0.40);
      goto exit;
VI:   picklag:=4.1+(4.3-4.1)×10×(r-0.50);
      goto exit;
VII:  picklag:=4.3+(4.6-4.3)×10×(r-0.60);
      goto exit;
VIII: picklag:=4.6+(5.0-4.6)×10×(r-0.70);
      goto exit;

```

IX: picklag:=5.0+(5.5-5.0)×10×(r-0.80);
goto exit;

X: if r<0.95 then picklag:=5.5+(5.9-5.5)×
10×2×(r-0.90) else picklag:=5.9+(7.0-
5.9)×10×2×(r-0.95);

exit:

end of picklag;

for REPEAT:=1 step 1 until N do
begin integer yy,zz;
 for yy:=1,2 do data[REPEAT,yy]:=read(20);
 for zz:=1 step 1 until data[REPEAT,2]
 do data[REPEAT,2+zz]:=read(20);
 for yy:=15 step 1 until 37 do data
 [REPEAT,yy]:=read(20);
end;

check:=read(20); close(20);

if check≠-1000 then
begin writetext(30,[[c]error*in*data]);
 goto reject
end;

begin for REPEAT:=1. step 1 until N do
maxlhq:=GAP:= DELAY:= LHLANEQ:= MOVETURN:=
RTSAT1:=RTSAT2:=AHEAD:= LTSASAT1:=LTSASAT2:=
FOLLOW:=ARRIVE:=STREAMBQ:=STOPTURN:=RTVS:=
LTSAVS:=TIME:= sattime1:=sattime2:=OPPDELAY:=

0;

DELVEH:=RHLANEQ:=cheat1:=cheat2:=maxrhq:=0;
head:=1;

for i:=1 step 1 until 1000 do Q[i]:=0;

run:=data[REPEAT,1];


```

print:=data[REPEAT,2];
for p:=1 step 1 until print do thyme[p]:=data
[REPEAT,2+p];
t:=data[REPEAT,15];
y0:=data[REPEAT,16];
cycle:=data[REPEAT,17];
red:=data[REPEAT,18];
amber:=data[REPEAT,19];
green:=data[REPEAT,20];
early:=data[REPEAT,21];
late:=data[REPEAT,22];
losttime:=data[REPEAT,23];
sLH:=(data[REPEAT,24]/3600)*t;
sRH:=(data[REPEAT,25]/3600)*t;
VA:=data[REPEAT,26];
rt:=data[REPEAT,27];
sa:=data[REPEAT,28];
sB:=(data[REPEAT,29]/3600)*t;
VB:=data[REPEAT,30];
moving:=data[REPEAT,31];
stopped:=data[REPEAT,32];
mingap:=data[REPEAT,33];
riteturn:=data[REPEAT,34];
cheet1:=data[REPEAT,35];
cheet2:=data[REPEAT,36];
rush:=data[REPEAT,37];

writetext(30,[RUN*NUMBER*]);
write(30,format([ndddcc]),run);

writetext(30,[INPUT[cc]]);

writetext(30,[SCAN*INTERVAL***SECS*=*]);
write(30,format([ndd.ddcc]),t);

writetext(30,[FIRST*RANDOM*NUMBER*=*]);
write(30,format([ddsdddsdddsddcc]),y0);

writetext(30,[CYCLE*TIME*SECS*=*]);
write(30,format([ndddc]),cycle);

writetext(30,[RED*TIME***SECS*=*]);
write(30,format([ndddc]),red);

writetext(30,[AMBER*TIME*SECS*=*]);

```

8

```

write(30,format([_ndddc_]),amber);

writetext(30,[_GREEN*TIME*SECS*=_]);
write(30,format([_ndddc_]),green);

writeext(30,[_early*cutoff*secs*=_]);
write(30,format([_ndddc_]),early);

writetext(30,[_late*start*secs*=_]);
write(30,format([_ndddc_]),late);

writetext(30,[_LOST*TIME**SECS*=_]);
write(30,format([_ndddcc_]),losttime);

writetext(30,[_VOLUME*ROAD*B*****VPH*=_]);
write(30,format([_nddddc_]),VB);

write text(30,[_VOLUME*ROAD*A*****VPH*=_]);
write(30,format([_nddddc_]),VA);

write text(30,[_VOLUME*ROAD*A*RHLANE*VPH*=_]);
write(30,format([_nddddc_]),(VAX(rt+sa)));

write text(30,[_MINIMUM*HEADWAY*SECS*=_]);
write(30,format([_ndd.ddcc_]),mingap);

writetext(30,[_TIME*TAKEN*BY*STOPPED*VEHICLE*
TO*CLEAR*STOPLINE*SECS*=_]);
write(30,format([_ndd.ddc_]),stopped);

writetext(30,[_TIME*TAKEN*BY*MOVING*VEHICLE*
TO*CLEAR*STOPLINE*SECS*=_]);
write(30,format([_ndd.ddcc_]),moving);

write text(30,[_PROPORTION*OF*RIGHT*TURNING*
VEHICLES[11s]=_]);
write(30,format([_d.dddc_]),rt);

write text(30,[_PROPORTION*OF*STRAIGHT*AHEAD*
VEHICLES*IN*RHLANE*=_]);
write(30,format([_d.dddc_]),sa);

writetext(30,[_PROPORTION*OF*VEHICLES*IN*
LHLANE[16s]=_]);

```


9

```

write(30,format([d.dddc]),(1-(sa+rt)));

writetext(30,[PPN*OF*VEHS*TURNING*IN*FRONT*OF
*OPPOSING*QUEUE*WHEN*FIRST*VEHICLE*IN*RIGHT*
HAND*QUEUE*IS*RIGHT*TURNING*==*]);
write(30,format([d.dddc]),rush);

effgreen:=green+amber-losttime;
c:=0; d:=1;
r:=random(c,d,y0);
z0:=0;
RED:=false; GREEN:=true;
gs:=pickgap; gm:=picklag;
k:=0;

```

```

kay: k:=k+1;
Start: if TIME>thyme[k] then goto Stop;
TIME:=TIME+t;
cycltime:=(TIME/cycle-entier(TIME/cycle))*
cycle;
if cycltime > (cycle-effgreen) then ASPECT:=
true else ASPECT:=false;
if (ASPECT eqv GREEN) and ((late > 0 and
cycltime < (cycle-effgreen+late)) or (early
> 0 and cycltime > (cycle-early))) then
FILTER:=true else FILTER:=false;
GAP:=GAP-t;
if STREAMBQ<0 then STREAMBQ:=0;
DELAY:=DELAY+(LHLANEQ+RHLANEQ)*t;
OPPDELAY:=OPPDELAY+STREAMBQ*t;
if MOVETURN>0 then MOVETURN:=MOVETURN-t;
if STOPTURN>0 then STOPTURN:=STOPTURN-t;
if AHEAD>0 then AHEAD:=AHEAD-t;
if FOLLOW>0 then FOLLOW:=FOLLOW-t;
ARRIVE:=ARRIVE-t;
if LHLANEQ > maxlhq then maxlhq:=LHLANEQ;

if ARRIVE > 0 then goto L1 else ARRIVE:=
ARRIVE+(mingap-(3600/VA-mingap)*ln(random(c,
d,z0)));

```

10

```

r:=random(c,d,z0);
if r>(rt+sa) then goto L26 else if r>rt then
  goto L25;

if ASPECT eqv RED then goto L4;

if FILTER then
  begin
    if RHLANEQ>0 or MOVETURN>0 or STOPTURN
      >0 or AHEAD0 then
        begin
          queue(1,true,alarm);
          DELVEH:=DELVEH+1;
          goto L40;
        end
      else
        begin
          RTVS:=RTVS+1;
          if FOLLOW>0 then
            begin
              MOVETURN:=MOVETURN+stopped;
              RTSAT2:=RTSAT2+1;
              sattime2:=sattime2+stopped;
              FOLLOW:=MOVETURN;
              if LHLANEQ>0 then
                begin
                  RTSAT1:=RTSAT1+1;
                  sattime1:=sattime1+
                    stopped .
                end;
            end;
          if GAP<0 then
            begin
              GAP:=GAP+(mingap-(3600/VB-
                mingap)*ln(random(c,d
                  z0)));
              STREAMBQ:=STREAMBQ+1;
            end;
            goto L11;
          end;
        end;
      end;

    if RHLANEQ>0 then
      begin
        queue(1,true,alarm);

```



```

        DELVEH:=DELVEH+1;
    end
    else goto L7;

L29:  if Q[head]=0 then goto L9;

        if STREAMBQ<0 then goto L10 else STREAMBQ:=
            STREAMBQ-sB;

L12:  if GAP>0 then goto L11 else
        begin
            STREAMBQ:=STREAMBQ+1;
            GAP:=GAP+(mingap-(3600/VB-mingap)*ln
                (random(e,d,z0)))
        end;

L11:  if LHLANEQ>0 then
        begin
            LHLANEQ:=LHLANEQ-sLH;
            LTSAVS:=LTSAVS+sLH;
            if MOVETURN>0 or STOPTURN>0 or AHEAD>0
            then
                begin
                    LTSASAT1:=LTSASAT1+sLH;
                    sattime1:=sattime1+t
                end;
            if RHLANEQ>0 or MOVETURN>0 or STOPTURN
                >0 or AHEAD>0 then
                begin
                    LTSASAT2:=LTSASAT2+sLH;
                    sattime2:=sattime2+t
                end;
            end;
        end;
        if cheat1=1 then
        begin
            if (ASPECT eqv GREEN) and ((TIME/cycle-
                entier(TIME/cycle))*cycle)<(cycle-
                effgreen+1.5*t) and RHLANEQ>0 and
                Q[head]=1 and r>rush then
                begin
                    queue(1,false,alarm);
                    RTVS:=RTVS+1;
                    cheat1:=cheat1+1
                end;
            end;
        end;
        goto Start;

```

2

```

L10: if STOPTURN>0 or MOVETURN>0 or AHEAD>0 then
      goto L11;
      if GAP<0 then
      begin
          GAP:=GAP+(mingap-(3600/VB-mingap)×
              ln(random(c,d,z0)));
          goto L11
      end;

      if FOLLOW<0 or FOLLOW>t then goto L38;
      if GAP>gm then goto L15 else goto L11;

L38: if GAP>gs then
      begin
          STOPTURN:=STOPTURN+stopped;
          FOLLOW:=STOPTURN+t;
          queue(1,false,alarm);
          RTVS:=RTVS+1;
          gs:=pickgap;
          if LHLANEQ > 0 and RHLANEQ>0 then
          begin
              RTSAT2:=RTSAT2+1;
              RTSAT1:=RTSAT1+1
          end;
          end;
          goto L11;

L15: MOVETURN:=MOVETURN+stopped;
      FOLLOW:=MOVETURN+t;
      queue(1,false,alarm);
      RTVS:=RTVS+1;
      gm:=picklag;

      if LHLANEQ>0 then
      begin
          RTSAT1:=RTSAT1+1;
          RTSAT2:=RTSAT2+1;
      end;
      goto L11;

L9: if STOPTURN>0 or MOVETURN>0 or AHEAD>0 then
      goto L16;
      if LHLANEQ>0 then

```


13

```

begin
    LTSASAT1:=LTSASAT1+1;
    LTSASAT2:=LTSASAT2+1;
end;

queue(0,false,alarm);
AHEAD:=AHEAD+1/sRH;
FOLLOW:=AHEAD+t;
LTSAVS:=LTSAVS+1;

L16: if STREAMBQ>0 then
    begin
        STREAMBQ:=STREAMBQ-sB;
        if GAP>0 then goto L11 else
            begin
                GAP:=GAP+(mingap-(3600/VB-mingap)
                    xln(random(c,d,z0)));
                STREAMBQ:=STREAMBQ+1;
                goto L11 .
            end;
        end;
    else
        begin
            if GAP<0 then GAP:=GAP+(mingap-(3600/VB
                -mingap)xln(random(c,d,z0)));
            goto L11
        end;
    end;

L7: if STOPTURN>0 or MOVETURN>0 or AHEAD>0 then
    begin
        queue(1,true,alarm);
        DELVEH:=DELVEH+1;
        goto L11;
    end
    else goto L21;

L20: queue(1,true,alarm);
    DELVEH:=DELVEH+1;
    goto L12;

L21: if STREAMBQ>0 then
    begin
        STREAMBQ:=STREAMBQ-sB;
        goto L20 .
    end;

```

12

```

L22: if GAP>0 then goto L23 else
      begin
          GAP:=GAP+(mingap-(3600/VB-mingap)×
              ln(random(c,d,z0)));
          queue(1,true,alarm);
          DELVEH:=DELVEH+1;
          goto L11
      end;

L23: if GAP>gm then
      begin
          RTVS:=RTVS+1;
          if FOLLOW>0 then
              begin
                  MOVETURN:=MOVETURN+stopped;
                  RTSAT2:=RTSAT2+1;
                  sattime2:=sattime2+stopped;
                  FOLLOW:=MOVETURN;
                  if LHLANEQ>0 then
                      begin
                          RTSAT1:=RTSAT1+1;
                          sattime1:=sattime1+stopped
                      end;
                  end;
              end;
              goto L11;
          end
      else goto L20;

L4:   queue(1,true,alarm);

L24:  DELVEH:=DELVEH+1;

L35:  if cheet2=1 then
      begin
          if (ASPECT eqv RED) and (TIME/cycle-
              entier(TIME/cycle))×cycle<t and RHLANEQ
              >0 and Q[head]=1 then
              begin
                  queue(1,false,alarm);
                  RTVS:=RTVS+1;
                  cheet2:=cheet2+1;
                  if Q[head]=1 and RHLANEQ>0 then
                      begin
                          queue(1,false,alarm);

```



```

RTVS:=RTVS+1;
cheat2:=cheat2+1
end;
end;
end;

if GAP<0 then
begin
    GAP:=GAP+(mingap-(3600/VB-mingap)*
        ln(random(c,d,z0)));
    STREAMBQ:=STREAMBQ+1
end;
goto Start;

L25: if ASPECT eqv RED then goto L27;
     if FILTER then
begin
    if RHLANEQ>0 or STOPTURN>0 or MOVETURN
        >0 or AHEAD>0 then
begin
        queue(0,true,alarm);
        DELVEH:=DELVEH+1;
end
    else LTSAVS:=LTSAVS+1;
    goto L40;
end;

L28: if RHLANEQ>0 then
begin
    queue(0,true,alarm);
    DELVEH:=DELVEH+1;
    goto L29;
end
    else
begin
    if STOPTURN>0 or MOVETURN>0 or AHEAD>
        0 then
begin
        queue(0,true,alarm);
        DELVEH:=DELVEH+1;
end
    else LTSAVS:=LTSAVS+1;
end;
goto L16;

```

11
2

```

L27:  queue(0,true,alarm);
      goto L24;

L26:  if ASPECT eqv RED then
      begin
          LHLANEQ:=LHLANEQ+1;
          goto L24;
      end
      else goto L33;

L33:  if LHLANEQ>0 then
      begin
          LHLANEQ:=LHLANEQ+1;
          DELVEH:=DELVEH+1;
          goto L34;
      end
      else
      begin
          LTSAVS:=LTSAVS+1;
          goto L34;
      end;

L34:  if RHLANEQ>0 then goto L29 else goto L16;

L1:   if ASPECT eqv RED then goto L35 else if
      FILTER then goto L40 else if RHLANEQ>0 then
      goto L29 else goto L16;

L40:  if GAP<0 then
      begin
          GAP:=GAP+(mingap-(3600/VB-mingap)×
              ln(random(c,d,z0)));
          STREAMBQ:=STREAMBQ+1;
      end;

      if RHLANEQ < 0 then goto L11;
      if Q[head]=1 then
      begin
          if STOPTURN>0 or MOVETURN>0 or AHEAD>0
              then goto L11;
          if FOLLOW>0 then goto L15 else goto L38;
      end
      else
      begin

```



```

if STOPTURN>0 or MOVETURN>0 or AHEAD>0
then goto L11;
AHEAD:=AHEAD+1/sRH;
FOLLOW:=AHEAD+t;
queue(0,false,alarm);
LTSAVS:=LTSAVS+1;
if LHLANEQ>0 then
begin
LTSASAT1:=LTSASAT1+1;
LTSASAT2:=LTSASAT2+1;
end;
goto L11;
end;

```

```

Stop: writetext(30,[[p]SIMULATION*TIME*SECS*=*]);
write(30,format([nnddddc]),TIME);

writetext(30,[RESULTS[cc]]);

writetext(30,[NO*OF*VEHICLES*DELAYED[9s]=*]);
write(30,format([nnddsdddc]),DELVEH);

writetext(30,[TOTAL*DELAY[15s]SECS*=*]);
write(30,format([nnddsdddsddd.dd]),DELAY);

writetext(30,[ (road*a)*****]);
write(30,format([nnddsdddsddd.dd]),OPPDELAY);

writetext(30,[ (road*b)*****]);
write(30,format([nnddsdddsddd.dd]),OPPDELAY+
DELAY);
writetext(30,[ (road*a+road*b)[c]]);

writetext(30,[AVE*DELAY*PER*DISCHARGED*
VEH*SECS*=*]);
write(30,format([nnddsddd.dddc]),
DELAY/(LTSAVS+RTVS));

write text(30,[AVE*DELAY*PER*ARRIVED*VEH*
SECS*=*]);
write(30,format([nnddsddd.ddd]),DELAY/
(LTSAVS+RTVS+LHLANEQ+RHLANEQ));

```

```
writetext(30,[ (road*a)*****]);  
write(30,format([n d d d s d d d . d d d ]),  
OPPDELAY/((VB*TIME)/3600));  
writetext(30,[ (road*b)*****]);  
  
write(30,format([n d d d s d d d . d d d ]), (OPPDELAY+  
DELAY)/(LTSAVS+RTVS+LHLANEQ+RHLANEQ+(VB*  
TIME/3600)));  
writetext(30,[ (road*a*+*road*b)[c]]);  
  
writetext(30,[AVE*DELAY*PER*DELAYED*VEH*SECS  
*=*]);  
write(30,format([n d d d s d d d . d d c ]), DELAY/  
DELVEH);  
  
writetext(30,[NO*RIGHT*TURNERS*VEH*=*]);  
write(30,format([n d d d d c ]), RTVS);  
  
writetext(30,[NO*LEFT*AND*STRAIGHT*AHEAD*  
VEH*=*]);  
write(30,format([n d d d d c c ]), LTSAVS);  
  
write text(30,[NO*RIGHT*TURNERS*TURNING*IN*  
FRONT*OF*OPPOSING*QUEUE*=*]);  
write(30,format([n d d d d c ]), cheat1);  
  
writetext(30,[NO*RIGHT*TURNERS*TURNING*AFTER*  
LIGHTS*HAVE*CHANGED*TO*RED*=*]);  
write(30,format([n d d d d c c ]), cheat2);  
  
writetext(30,[MAX*RHLANE*QUEUE*LENGTH*VEH  
*=*]);  
write(30,format([n d d d d c ]), maxrhq);  
  
writetext(30,[NO*VEHS*REMAINING*IN*RH*QUEUE*  
AT*END*OF*SIMULATION*=*]);  
write(30,format([n d d d d c c ]), RHLANEQ);  
  
writetext(30,[MAX*LHLANE*QUEUE*LENGTH*VEH*  
*=*]);  
write(30,format([ - n d d d d . d d c ]), maxlhq);  
  
writetext(30,[NO*VEHS*REMAINING*IN*LH*QUEUE*  
AT*END*OF*SIMULATION*=*]);
```



```

write(30,format([_ndddd.ddcc]),LHLANEQ);

writetext(30,[[5s]SATURATION*FLOWS[cc]INPUT*
SATURATION*FLOW*LHLANE*****PCU*PER*HOUR*
=*]);
write(30,format([_ddddc]),(sLH×3600)/t);

writetext(30,[INPUT*SATURATION*FLOW*RHLANE***
*****PCU*PER*HOUR*=*]);
write(30,format([_ddddc]),(sRH×3600)/t);

write text(30,[INPUT*SATURATION*FLOW*OPPOSING
*ARM*PCU*PER*HOUR*=*]);
write(30,format([_ddddcc]),(sB×3600)/t);

write text(30,[BOTH*LANES[cc]NO*OF*RIGHT*
TURNERS[11s]VEH*=*]);
write(30,format([_nddddc]),RTSAT1);

write text(30,[NO*OF*LEFT*AND*STRAIGHT*AHEAD*
VEH*=*]);
write(30,format([_nddddc]),LTSASAT1);
write text(30,[SATURATION*FLOW*TIME*SECS*=*]);
write(30,format([_nddddc]),sattime1);

writetext(30,[saturation*flow*vph[c]uncompen
sated*for*longer*right*turning*maneuver*time
*=*]);
write(30,format([_nddddc]),((RTSAT1+LTSASAT1)
/sattime1)×3600);

writetext(30,[compensated*for*longer*right*
turning*maneuver*time*=*]);
write(30,format([_nddddc]),((RTSAT1+LTSASAT1)
×3600)/(sattime1-((stopped-1/sRH)×RTSAT1)));

writetext(30,[SINGLE*LANES[cc]NO*OF*RIGHT*
TURNERS[11s]VEH*=*]);
write(30,format([_nddddc]),RTSAT2);

write text(30,[NO*OF*LEFT*AND*STRAIGHT*AHEAD*
VEH*=*]);
write(30,format([_nddddc]),LTSASAT2);

```

```

writetext(30,[SATURATION*FLOW*TIME*SECS*=_]);
write(30,format([_nddddcc_],sattime2);

writetext(30,[saturation*flow*vph*=_]);
write(30,format([_nddddcc_],((RTSAT2+LTSASAT2)
  x3600)/sattime2);

writetext(30,[right*turning*vehicle*factor
  *=_]);
if RTSAT2 $\neq$ 0 then
  begin
    pcu:=(((sLH+sRH)/t)x sattime2-LTSASAT2)
      /RTSAT2;
    write(30,format([_nddd.dddcc_],pcu);
  end
  else writetext(30,[infinite[cc]]);

writetext(30,[[17s]degrees*of*saturation
  [cc17s]road*a[38s]road*b[c]right*turn*factor
  *****input*volumes*****output*volumes[5s]
  input*volumes*only***no*right*turners[c6s]
  ]);
write(30,format([_nddd.ddd_],riteturn);
writetext(30,[[10s]]);
write(30,format([_ndd.ddd_],(VAXt*(1+(rite
  turn-1)xrt))/((effgreen/cycle)x(sRH+sLH)x
  3600)));
writetext(30,[[12s]]);
write(30,format([_ndd.ddd_],((LTSAVS+RTVSx
  riteturn)x t)/((effgreen/cycle)x(sLH+sRH)x
  TIME)));
writetext(30,[[7s]]);
write(30,format([_ndd.dddcc_],(VBxtxcycle)/
  (sBx3600x(effgreen-late-early))));
writetext(30,[[6s]]);

if RTSAT2=0 then writetext(30,[infinity[cc]])
  else
    begin
      write(30,format([_nddd.ddd_],pcu);
      writetext(30,[[10s]]);
      write(30,format([_ndd.ddd_],(VAXt*(1+
        (pcu-1)xrt))/((effgreen/cycle)x(sRH+
        sLH)x3600)));
      writetext(30,[[12s]]);
    end
  end

```



```

write(30,format([ndd.ddddcc]),((LTSAVS
+RTVSXpcu)xt)/(TIMEX(effgreen/cycle)x
(sLH+sRH)));
end;

begin comment To calculate delays by RRL
formula;
real d,lamda,x,d2,lamda2,x2;
writetext(30,[THEORETICAL*DELAYS*
CALCULATED*BY*RRL*FORMULA[cc]]);
lamda:=effgreen/cycle;
lamda2:=1-(effgreen+late+early)/cycle;
writetext(30,[RIGHT*TURNING*VEHICLE*
FACTOR*=*]);
write(30,format([nd.ddddc]),riteturn);
x:=(VAX(tx(1+(riteturn-1)xt)))/(lamdax
(sRH+sLH)x3600);
x2:=(VBxt)/(lamda2xsBx3600);
if x<1 then
begin
d:=(cyclex(1-lamda)2/(2x(1-lamda
xx)))+(x2/(2xVAX(1-x)))-0.65x
((cycle/VA2)(1/3))x(x(2+5x
lamda));
writetext(30,[DELAY*PER*VEHICLE[
9s]=*]);
write(30,format([nddd.ddddc]),d);
write text(30,[DELAY*PER*DELAYED*
VEHICLE*=*]);
write(30,format([nddd.ddddcc]),
(dxVAXTIME)/(DELVEHx3600));
end
else writetext(30,[DELAY*INFINITE***
APPROACH*OVERSATURATED[c]]);

writetext(30,[opposing*approach[cc]
delay*per*vehicle*=*]);
if x2<1 then
begin
d2:=(cyclex(1-lamda2)2/(2x(1-
lamda2xx2)))+(x22/(2xVBx(1-x2)))
-0.65x((cycle/VB2)(1/3))x(x22

```

```

(2+5×lamda2));
write(30,format([-nddd.ddddp]),d2);
end
else writetext(30,[infinite*delay**opp
osing*approach*oversaturated[p]]);
end of RRL delays;

goto finish;

alarm:writetext(30,[ [p]RHLANEQ*OVERLENGTH*1000*VEH
. [c]TIME*=[ ] );
write(30,format([nddddc]),TIME);
goto Stop;

finish: if k < print then goto kay;

end of REPEAT;
end program;

reject:close(30);

end→

```


2.4.5 Input

Information is input to the program in the form of Algol numbers, separated by semicolons, and punched on eight-hole paper tape. The data should be punched in the order described at the beginning of the program under the first 'comment'. An example print out of a data tape is shown as fig.

2.21, for two runs.

2.4.6 Output

The output is in two phases. The first phase merely outputs the data before any simulation is attempted, and it is called once only at the beginning of each run (an example is shown as fig. 2.22). The second phase outputs the results of the simulation from the start up to each printout time specified on the data tape, and an example is shown as fig. 2.23. The quantities output are:

1. Simulated time to which the items below apply. It should be noted that where two or more sets of output are given for the same run, the second and subsequent sets of results all apply from the start of the simulation, and not from the previous print out time.
2. This item is a count of the number of vehicles joining the queues on the approach arm only - no such count was taken for the opposing arm.
3. The total time spent by vehicles on the approach arm in either of the queues (in veh/s).

4. As for 3, but for the opposing arm.
5. The sum of 3 and 4, i.e. the total time spent in queueing on the approach and opposing arms.
6. This is 3 divided by the number of vehicles clearing the stop line on the approach arm only.
7. 3 divided by the number of vehicles discharged and the number of vehicles remaining in the queues on the approach arm (items 16 and 18).
8. Total delay on the opposing approach (4) divided by the input opposing volume up to the appropriate simulation time.
9. The average delay per arrived vehicle for both the approach and opposing arms computed as for 7 and 8. (N.B. NOT the sum of 7 and 8.)
10. 3 divided by 2.
11. The number of right turning vehicles that cross the stop line on the approach arm.
12. The number of straight ahead vehicles that cross the stop line on the approach arm.
- 13, 14. See Section 2.3.3 for an explanation of these two quantities.
15. The maximum length attained by the right hand lane queue during the simulation.

16. The number of vehicles generated (output to enable a comparison to be made with the number of vehicles requested on the data tape).
17. As 15, but for the left hand lane queue.
18. As for 16, but for the left hand lane queue. It is possible for this quantity to go to less than zero, but only by a small amount. This negative quantity is subtracted from the next vehicle when it joins the queue, and so no errors are introduced over a long period - only in one cycle taken in isolation.
- 19,20,21. Saturation flows merely copied from the data tape. They belong, strictly speaking, to phase 1.
22. The number of right turning vehicles discharged under 'both lane' saturation flow conditions.
23. The number of (left turning) straight ahead vehicles discharged under 'both lane' saturation flow conditions.
24. The time for which 'both lane' saturation flow conditions obtain.
25. $((22) + (23)) / (24)$.

26. As for 25., except that the time (24) is reduced by the difference in manoeuvring time between right turning vehicles and straight ahead vehicles multiplied by the number of right turning vehicles.
- 27, 28,
29, 30. As for 22, 23, 24 and 25, except for 'single-lane' saturation flow conditions.
31. Calculated as described in Section 2.3.5.
32. The right turning vehicle factor assumed in the calculation of delays using the RRL formula. (All degrees of saturation are calculated, using the methods described in ref. 2.6 and 2.7, for two values of right-turning vehicle factor.)
33. Degrees of saturation calculated from the input volume for the approach arm and item 32.
34. Degree of saturation calculated from items 11, 12, 16, 18, and 32 for the approach arm.
35. Degree of saturation for the opposing arm based upon input volumes only.
36. Item 31 repeated
37. As for 33, but using item 36.
38. As for 34, but using item 36.

39. As for 32.

40. Delay calculated from the Road Research Laboratory formula given in ref. 2.6.

41. Computed from 40, the input approach volume and 2.

42. As for 40, but for the opposing arm.

2.4.7 Size

The size of the program, when compiled by the Kidsgrove compiler, is about 6048 words. Peripheral equipment required by the program is

- i) One tape reader required once only at the beginning of a series of runs.
- ii) One line printer at intervals throughout the series of runs.

No magnetic tape or disc storage is required.

2.4.8 Running Times

The running time will vary according to the amount of data to be input and output, but an average run time is 1 hour traffic simulated in 17s, when the program is established using the Kidsgrove compiler.

2.5 PROGRAM TESTING

Tests performed on the program were of two types. The first - termed 'mechanical tests' (Section 2.5.1) - were performed to check whether the program was functioning in the manner intended. The second type - termed 'calibration tests' (Section 2.5.2) - were performed to check the accuracy of the program against field conditions. (For convenience, a set of input conditions and the resulting output quantities are hereafter referred to by a particular 'run number'. The input data for each 'run' differs in at least one item from every other 'run'. Full details of the input data and output results are given in Appendix V11.)

2.5.1 Mechanical Tests

The first test was to check whether the output, simulated, saturation flows were similar to the input saturation flows. No right turns were allowed, and the approach was loaded with a volume sufficient to ensure that a queue was present most of the time (see Appendix V11, run number 9 for full details of the input data). The result was a simulated saturation flow higher than the input saturation flow of 3200 veh/h (see Table 2.9). Further checks were made using similar traffic loadings and different starting random numbers, and all produced flows slightly too high (see Table 2.9 and Appendix V11, runs 17 and 124-128). The mean of the output saturation flows was 3268 veh/h. The input saturation flow for these runs was 3200 veh/h, and therefore a 2% error is present. This error is insignificant, however, when compared with the scatter in the results produced by using different starting random numbers. (Calculated by applying the Chi-squared test to the results using the output, or simulated, saturation flow as the observed value and the input saturation flow as the expected value. Chi-squared = 12.62, which is insignificant at the 5% level.) The error is introduced because of the different methods of queue discharge used in the model. It may be seen from Section 2.3.4, that vehicles are subtracted from the left hand queue as fractions of vehicles at every scan interval,

whereas vehicles are subtracted from the right hand queue as whole vehicles at groups of scan intervals. The mixture of these two queue extraction methods produces variations in the output saturation flows, and the error will be introduced every time one or other of the queues empties. This means that the effect is additive, and will not be eradicated by using a long simulation time.

A further check on this effect may be obtained by examination of the output 'two-lane' saturation flows, compensated for the slower turning rate of right turning vehicles (see Section 2.3.5 for a fuller discussion of saturation flows). The results for the first set of production runs (those with no special turning phase - runs 18-65) are shown in Table 2.10, and the mean of these values is 3233 veh/h - an error of 1%. A t-test showed that this error was not significant at the 5% level.

It would be possible to remove this error by rewriting the program so that both queues were serviced by the same extraction procedure, i.e. by extracting vehicles one at a time at intervals proportional to the input saturation flow, as the right hand lane queue is serviced at present, or by extracting fractions of vehicles at each scan interval, as the left hand lane queue is serviced at present. It was felt, however, that the time and effort necessary in programming and 'debugging' was not warranted by the correction of such a small error.

A second check on the model was one where the opposing flow was set to 1 veh/h (the lowest value attainable) and all the vehicles in the right hand lane of the approach arm were right turning vehicles (run number 10). This test produced a compensated saturation flow of 3201 veh/h. Nine further checks were made using similar traffic loadings but different starting random numbers (runs 134, 135, 137-143), and the effect of the different random numbers is shown in Table 2.11. The error in the simulated value is 13 veh/h (0.4%), which is insignificant at the 5% level when tested by the Chi-squared test. Again, the scatter in these results is produced by the differences in the queue clearance mechanisms, and the remarks made above about the first mechanical test apply here. The scatter in

the results appears to be smaller than in the first test, but since small samples are being used, no definite conclusions have been drawn. It would be possible to check this point further, but at the expense of more computer time.

The third check (run no. 11) was to simulate the situation where right turning vehicles only were in the right hand lane, opposed by a very heavy opposing flow (1600 veh/h). The result simulated was the result expected - i.e. the right hand lane was completely blocked leaving only the left hand lane free to discharge. The simulated saturation flow was 1600 veh/h, equal to the input saturation flow for the left hand lane. Four similar runs were made using similar traffic conditions, but different starting random numbers were used. No variations in the figure of 1600 veh/h were noted.

2.5.2 Calibration Tests

Observations were made at the A1/Clayton Road intersection on Monday, 28th February, 1966 between 1700 and 1800 hours, and on Thursday, 10th March, 1966 between 1645 and 1800 hours. The periods of observation were split into 30 minute intervals and 15 minute intervals respectively, and observations were made of:-

- i) The saturation flow at the north bound stop line (the saturation flow was calculated for the situation where the left hand lane queue was discharging and when vehicles were present in the right hand lane queue, discharging or not).
- ii) The opposing flow (vehicles were classified into the usual groups).
- iii) The signal timings.
- iv) The volume of right turning vehicles at the north bound stop line.

- v) The number of vehicles using each lane of the north bound approach.

Gap acceptance characteristics were assumed to be those observed on earlier occasions, and vehicles were allowed to cross the stop line in front of the opposing traffic at the start of the green and at the end of the green as observed on earlier occasions.

The above observations, apart from the saturation flows, were then used as input to the program and the simulated saturation flows compared with those observed. The input data are shown in Table 2.12, and the observed and simulated saturation flows compared in Table 2.13. Results were obtained from the simulation at various time intervals to indicate how the model was settling down, the queues in the model at the start of the simulation being empty. Runs 2 and 6 (see Table 2.13) produced acceptable results, but results from the other runs are rather inconclusive. However, as may be seen from Table 2.12, the input flows varied wildly over the observation period, and since the saturation flows were, in most cases, only based upon 15 minute observation, the observed saturation flows may be subject to substantial sampling errors.

A further check on the model was provided by observations made at traffic signals at the junction of Wilmslow Road/Moseley Road/Wilbraham Road at Fallowfield, Manchester. Observations were made at the south bound approach during the evening peak hour on Thursday, 16th May, 1967. The procedure was similar to that employed in the observations in Newcastle upon Tyne, and the input conditions are shown in Table 2.12 under run number 913. The results of the simulation are shown in Table 2.13 under the same run number. Gap acceptance characteristics were assumed to be similar to those observed in Newcastle upon Tyne.

No further field checks were made on the program, principally because of the difficulty of observing steady traffic conditions over a reasonable length of time: indeed, this is the very problem that the program is designed to overcome. No trend was observed when comparing the simulated and observed results - some simulated results were too large, and others too

small. The average error was 7%, the errors ranged from 1.5% to 16.0%, and they were held to be reasonable. It was concluded, therefore, that the model reproduced actual traffic conditions satisfactorily, and formed a reasonable basis for the prediction of traffic behaviour.

2.5.3 Simulation Times and Random Numbers

Five runs (12-16) were carried out using identical traffic conditions, but with different starting random numbers, to find the shortest simulation time necessary to reduce the effect of the starting random number to acceptable levels. The random numbers were taken, at random, from random number tables given in ref. 2.28. The numbers and the runs in which they were used, are shown in Table 2.14. The input traffic conditions were set at typical values (see Appendix V11) for each run, the only variable being the starting random number. The effects of the starting number and simulation time are shown on fig. 2.24, and it may be seen that no improvement in the convergence of the lines is obtained after a simulation time of 5h. This time of 5h was accordingly selected as the most economical simulation time. The data relevant to fig. 2.24 is shown in Table 2.15.

Table 2.16 shows the means of the simulated saturation flows, together with confidence limits for these means at various confidence levels. It may be seen from Tables 2.15 and 2.16 that runs 13 and 15 exceed the 95% confidence limits, and also that the input 'two-lane' saturation flow rate, 3200 veh/h, is only included in the limits at the 99.9% level of confidence. It should be remembered, however, that these conclusions are drawn from a small sample (5).

On the basis of the remarks made in the above sections, then, it was concluded that although the model could not reproduce fine variations in observed traffic behaviour, it formed a reasonable imitation of the real life situation. Predictions of traffic behaviour made with the model are detailed in the following sections.

2.6 PRODUCTION RUNS

It was decided to use the model to investigate the effect of opposing flow on the saturation flow on the north bound stop line of the intersection. Runs 17-65 were used to investigate the situation where no special right turning phase was provided: 66-113 for a similar situation with a nine second special phase (early cut-off). Input data for these runs were as follows:

1. Scan interval : 1s
2. First random number : See Table 2.14
3. Cycle time : 60s
4. Red time : 30s
5. Amber time : 3s
6. Green time : 27s
7. Early cut-off time : 0s, 9s
8. Late start time : 0s
9. Lost time per phase : 0s
10. Saturation flow in left hand approach lane : 1600 veh/h.
11. Saturation flow in right hand approach lane : 1600 veh/h.
12. Approach volume : 900 veh/h.
13. Proportion of right turning vehicles in approach : Varies between 0-30% in 5 per cent increments.
14. Proportion of straight ahead vehicles in right hand lane : Varies so as total traffic in right hand lane is constant @ 30%

15. Saturation flow on
opposing arm : 3200 veh/h.
16. Opposing volume : Varies between 1 and 1200
veh/h.
17. Moving vehicle clearance
time : 1s
18. Stopped vehicle clearance
time : 2.3s
19. Minimum headway : 1s
20. Right turning vehicle factor
for delay calculations : 1.75
21. No vehicles were allowed to
discharge at the beginning or
end of the green period.

The input data above was chosen so as to be reasonably close to conditions at the model site, in order to make comparison easier. No special right turning phase was provided at the model site, and so the figure of 9s early cut-off time was calculated using the methods recommended in ref. 2.3, for average conditions.

2.7. RESULTS

2.7.1 Right Turning Vehicle Factor

The simulated values of right turning vehicle factors for the two sets of production runs (those with no special right turning phase runs 17-65, and those with 9s early cut-off - runs 66-113) are shown in Table 2.17, and diagrammatically on figs. 2.25-2.30. Fig. 2.31 shows all the data plotted on a single diagram. Also shown on fig. 2.31 are two regression lines: one is a regression line through all the data for no special right turning phase, and the other through all the data where the early cut-off was provided. These two lines are shown as chain dotted lines, and they are repeated on figs. 2.25-2.30 as chain dotted lines. Also shown on figs. 2.25-2.30 are the two further regression lines: one is the regression line through the data for no special right turning phase at the particular proportion of right turning vehicles shown on the diagram (the solid line), and the other (the dashed line) the regression line through the early cut-off data at that particular right turning proportion.

The parameters for the regression lines are shown in Table 2.18. A logarithmic transformation of the ordinate - the right turning vehicle factor - was made to bring the data into an approximately linear form:-

$$\text{Log } y = a + bx$$

where y is the right turning vehicle factor,

a and b are regression constants,

and x is the opposing flow.

The true equation of the lines is therefore of the form:-

$$y = \exp(a + bx)$$

Also shown in Table 2.18 are the correlation coefficients (r) and variance ratios (F). All values of r and F were significant at the 0.1% level.

(F is used as a test for the linear dependence of y on x .)

An analysis of variance was carried out on the data for when no special right turning phase was provided (runs 18-65). The results are shown in Table 2.19. (In Table 2.19, a 'treatment' is the data for a particular proportion of right turning vehicles. A 'block' is the data for a particular value of opposing flow. Thus there are six treatments and eight blocks.) The results of this test imply that the right turning vehicle factor is dependent upon both the proportion of right turning vehicles, and the opposing flow. This supposition is supported by the data shown in Table 2.20 and analysed in Table 2.21. The data (runs 114-123) was obtained to investigate the scatter in the simulated right turning vehicle factor produced by using different starting random numbers. Input data was similar to all the other production runs. The opposing flow was fixed at 600 veh/h, the proportion of right turning vehicles fixed at 15%, and no special right turning phase was provided. The confidence limits of the right turning vehicle factor were calculated for the conditions described above, and are shown in Table 2.21. Inspection of Table 2.21 shows that the confidence limits are quite 'tight', and inspection of Table 2.17 shows that the simulated right turning vehicle factors at an opposing flow of 600 veh/h and right turning vehicle proportions of 10% and 20% are not included within these confidence limits. It may be concluded, then, from the analysis of variance, and the confidence limits, that the data for one proportion of right turning vehicles is significantly different from another.

However, statistical tests on the regression lines showed that

- i) None of the lines for any particular proportion of right turning vehicles was significantly different from the line drawn through all the data, for the condition where no special right turning phase was provided.
- ii) None of the lines for any particular proportion of right turning vehicles was significantly different from the

line drawn through all the data, for the condition where the early cut off was provided.

The above apparently contradicts the result of the analysis of variance test detailed in Table 2.19, and there are two possible reasons for this. One is that the logarithmic transformation 'masks' the variation in the data, and the other is that the data is not adequately represented by the lines drawn through them, despite the highly significant correlation coefficients shown in Table 2.18. Inspection of figs. 2.25-2.30 shows that, although the logarithmic transformation along the ordinate axis satisfactorily reduces the data to linear form at low values of right turning proportions, e.g. fig. 2.25, it becomes less satisfactory at higher right turning proportions. Indeed, the data shown in fig. 2.30 shows a distinct curvature, despite the logarithmic transformation. (This criticism applies more strongly to the data for which no special right turning phase was provided - where the early cut off was provided, the data exhibit a more linear form, as shown by the correlation coefficients in Table 2.18.)

It may reasonably be concluded, therefore, that the proportion of right turning vehicles does have a significant effect on the right turning vehicle factor, although the effect of opposing flow is much stronger.

Analysis of the regression lines also showed that the slopes of the lines shown on fig. 2.31 - the lines drawn through all the data for each signal condition - were not significantly different. This means that the introduction of the early cut off made no significant difference to the right turning vehicle factor. This result is somewhat surprising, since inspection of figs. 2.25 - 2.30 shows that the line drawn for the early cut off conditions is always below the other. Fig. 2.31, however, shows that the scatter in the data is considerable. The effect of the introduction of the early cut off on delay is discussed in Section 2.7.2.

The regression analysis also revealed that the 95% confidence limits for the intercept, a , for the mean lines were:-

-0.2515, -0.6337 where no right turning phase was provided, and, 0.2755, 0.0755 where the early cut off was provided.

These values are the logarithms of the true values, which are 0.759, 0.531, and 1.311 and 1.080 respectively. The true value of a is merely the ratio of the average headway in a stream of right turning vehicles and the average headway in a stream of straight ahead vehicles. In the case of the production runs in this work, therefore, the true value of a is $2.30/2.25$, or 1.022. The average simulated value is 1.162, and may be expected to be slightly higher because it is impossible in the model for a traffic volume to reduce to zero - a division is necessary in the gap generation procedure, and the introduction of a zero would cause a store to overflow. Accordingly the value unity was used instead of zero when specifying the opposing flow.

2.7.2 Saturation Flows and Degrees of Saturation

Simulated saturation flows ('single lane') are shown in Tables 2.22 and 2.23, and diagrammatically in figs. 2.32 and 2.33. It should be noted that the proportions of right turning vehicles indicated in these, and other, diagrams are nominal only - when the intersection becomes oversaturated because of increasing opposing flows, the proportion of vehicles actually able to turn right decreases, and the queue in the right hand lane increases. Degrees of saturation were output from the program based upon both the simulated right turning vehicle factor and the commonly assumed figure of 1.75, and they are shown in Table 2.24 and 2.25. The data from these tables for nominal right turning proportions of 10 and 30% are shown in fig. 2.34. (The other data for proportions of 5, 15, 20 and 25% have been omitted for clarity.) From fig. 2.34 and Tables 2.24 and 2.25, the opposing volumes at which the intersection becomes saturated have been listed in Table 2.26.

Inspection of Tables 2.22 and 2.23 shows that

- i) The effect of the proportion of right turning vehicles on saturation flow becomes less as the proportion increases; and
- ii) The effect of the 9s early cut off is negligible.

Conclusion ii) is reinforced by reference to Table 2.26 and fig. 2.34. It may be seen that the effect of the special right turning phase on the degree of saturation is negligible until the degree of saturation becomes greater than unity. Once this value of unity is reached, however, the situation is of no further interest to the practising traffic engineer because the intersection can no longer cope with the arriving traffic, and queues build up very quickly. Inclusion of the special phase would be of some value in a peak period of short duration, however, because it would allow the accumulated queues to clear more quickly once the arrival volumes had decreased.

2.7.3 Delay

The effect of opposing flow is shown for a right turning proportion of 15% in Table 2.27 and fig. 2.35 and 2.36. Four 'delays' are shown for each signal condition:

- i) Simulated delay per arrived vehicle.
This delay is found in the model by dividing the total delay on the approach arm by the number of vehicles discharged plus the number of vehicles in the queues. (The program also outputs the delay per discharged vehicle. This quantity is not shown in Table 2.27, but it will differ from the above when the degree of saturation exceeds unity.)
- ii) 'RRL delay'. This quantity is found by calculating the degree of saturation ^(x) of the approach using the simulated right turning vehicle factor, and inserting this value of x in the delay equation given in ref. 2.3 (p.48).
- iii) Average delay per arrived vehicle averaged over the approach and opposing arms. This quantity was found by summing the total delay on both approaches and dividing by the total number of arrived vehicles. It was considered important because any provision of special right turning phases on the approach arm would subtract green time from the opposing arm thereby increasing delay on that arm. In considering any improvements due to

provision of a right turning phase, it is necessary to consider the intersection as a whole. (The delay on the third arm will remain constant so long as the red time on the approach arm remains unaltered.)

iv) Delay per delayed vehicle on the approach arm. This quantity will approximate to the delay per discharged vehicle as the degree of saturation increases.

Runs 114 - 123 were used to investigate the reliability of the above results. Variations in the quantity (i) above are shown in Table 2.28, and Table 2.29 shows calculated confidence limits based upon the simulated results. (It should be remembered that the confidence limits shown in Tables 2.21 and 2.29 are based upon the assumption that the data is normally distributed. This may or may not be the case - unfortunately the amount of computer time necessary to test the validity of this assumption was held to be prohibitive.)

The curves shown on fig. 2.35 are for 15% right turning vehicles only, but the curves for other proportions of right turning vehicles are similar. The most distinctive feature is the very steep rise in delay over the values of opposing flow at which saturation occurs (cf. Table 2.25). Once the degree of saturation exceeds unity, the values of the average delay become meaningless because the intersection is overloaded and queues build up continuously. The truncation at the top of the curves is caused by the fact that the simulation program is automatically stopped when the right hand lane queue reaches 1000 vehicles - since during oversaturated conditions the delay will be proportional to the simulation time, and since the queue length will reach 1000 vehicles more and more quickly as the opposing flow increases, the delay curves tend to be cut off at delays of approximately 1500s. Delays of this order, apart from being rather artificial for the

reasons cited above, in any case represent quite intolerable traffic conditions. The downward trend in some of the curves between opposing flow values between 1 and 200 veh/h are caused by the scatter in the results due to the use of different starting random numbers - the effect is still present at higher opposing flow values, but is masked by the increasingly powerful effect of the increase in opposing flow. This downward trend is not evident in all of the curves, the only other being that for the 5% right turning condition.

As mentioned above, the important curves for comparison when investigating the effect of the early cut off are those averaging the delay over both the approach and opposing arms. The differences in these two curves at full saturation are shown in Table 2.30 for various proportions of right

turning vehicles. Although the scatter in the differences in delay is considerable, it may be seen from Table 2.30 that the difference is always positive, and greater than 20s. It may therefore be concluded that the introduction of the 9s early cut off has produce a beneficial improvement in average delay, (the saving of 20s/veh represents approximately 8 veh-h/h), although the effect of the special phase on capacity was small. This is presumably because, as the degree of saturation approaches unity, the average delay is extremely sensitive to small increases in the degree of saturation.

Inspection of fig. 2.36 shows that the delay curves predicted by the simulated degrees of saturation lie close together, but the curve applying to the early cut off situation lies above the other. This is obviously not the result expected, and contradicts the simulated delays. The reason for this discrepancy is that the Road Research Laboratory formula uses the degree of saturation to predict the average delay, and the simulated degrees of saturation were subject to considerable scatter (cf. Tables 2.24 and 2.25). The scatter was sufficient to mask any difference in the degrees of saturation due to the introduction of the right turning phase until the value of x exceeded unity, whereupon the difference became quite marked.

The discrepancy between the Road Research Laboratory predicted delay curves and the simulated delay curves at low opposing flow values is due to the difficulty of generating an exact hourly volume at low input volumes even when simulating for 5h. In the program's present form, the actual opposing flow is not output or stored - the average delay on the opposing approach is calculated using the total simulated delay on the approach and the input opposing volume.

2.7.4 Comparison With Other Work

Figs. 2.37 and 2.38 show the original Road Research Laboratory results of their observations of the effect of right turning vehicles on saturation flow (see Section 2.1.2, fig. 2.1 and ref. 2.2 for a detailed description of the derivation of the results). 'Relative saturation flow' in this context means

the saturation flow observed at a particular proportion of right turning vehicles expressed as a proportion of the saturation flow observed when 10% of the vehicles were right turning. This method of expressing the results was chosen because 10% was held to be an average figure at the time the results were taken (pre-1958).

Also shown on figs. 2.37 and 2.38 are some simulated results reduced to the same form for easy comparison. Pretty's (ref. 2.14, see Section 2.1.3) results have been used for two cases. First, an approach flow and opposing flow of 300 veh/h has been substituted in his equations and the results shown on fig. 2.37, and secondly, approach and opposing flows of 360 veh/h have been used for fig. 2.38. (Flows greater than 360 veh/h and turning proportions greater than 20% were outside the range for which his regression equations were valid.)

The author's results, shown on fig. 2.32, have been treated in a similar fashion, and they also are shown on figs. 2.37 and 2.38. Opposing flows of 300 and 360 veh/h respectively were used to enable easy comparison with Pretty's results. They are not exactly comparable because an approach flow of 900 veh/h was used in this work, as opposed to Pretty's values of 300 and 360 veh/h.

Inspection of fig. 2.37 and 2.38 shows that all sets of simulated results produce steeper gradients than the observed Road Research Laboratory results, indicating that the simulated results produce higher right turning vehicle factors. Direct comparison is difficult because of the difficulty of matching all the parameters which affect the right turning vehicle factor. The curves match tolerably well at right turning proportions greater than 10%, but at proportions lower than 10% the simulated results - both the author's and those of Pretty - produce gradients markedly steeper than that observed by the Road Research Laboratory.

The author's results have also been compared with the recommendations made in ref. 2.13 (Highway Capacity Manual), which are shown on fig. 2.2. The curve appropriate to stop line widths of 16 - 34 ft. has been re-drawn on fig. 2.39, together with the Road Research Laboratory curve.

The author's results for the case where no special right turning phase was provided (cf. Table 2.2) have been plotted at opposing flows of 1, 400 and 1200 veh/h and shown on the diagram. It may be seen that the curves, again, match tolerably well at right turning proportions higher than 10%, but note the difference in gradient between the HCM and RRL results and the author's result for an opposing flow of 1200 veh/h. This steep gradient indicates the very rapid reduction in saturation flow as the proportion of turning vehicles increases.

2.7.5 Application of Results and Conclusions

Areas of variability of the results left uninvestigated by this work include variations caused by changes in

- i) Cycle times
- ii) Proportion of green time
- iii) Approach widths
- iv) Approach volumes
- v) Lane distribution
- vi) Gap acceptance characteristics.

Items i) to v) are easily changed in the program by entering the new values as input data. Item vi) would require some simple programming changes. Despite the relatively high speed of the program, some simple arithmetic will quickly show that a thorough investigation of the effect of all the above variables on the right turning vehicle factor would require a considerable amount of computer time and even more analysis time, and so further investigations have not been attempted. The program is available, however, if any other investigator requires to use it. It is believed, despite the remarks above, that the most important quantities which affect the right turning vehicle factor have been thoroughly investigated in this work, i.e.

- i) Opposing flow
- ii) Proportion of right turning vehicles
- iii) Provision of a special right turning phase,

and an example use of the results is shown as Appendix V1. This appendix also includes an example of the recommended method (ref. 2.3) for calculating signal timings for a hypothetical intersection. The results of these calculations are summarised in Table 2.31. Inspection of Table 2.31 shows that the higher values of degrees of saturation produced by the use of the results of this work result in a longer cycle time and green time being recommended. This is because of the high right turning vehicle factors on the north and south approaches.

It has been argued in a private communication with F.V. Webster (ref. 2.49) that the model does not accurately simulate actual traffic conditions because of the strict lane discipline imposed: in the model, a vehicle waiting to turn right completely blocks the right hand lane, whereas in practice vehicles behind the waiting vehicle tend to squeeze past. This criticism of the model is accepted to some extent, and it is agreed that the model may tend to over estimate slightly the effect of a right turning vehicle at light turning movements. It is doubted, however, whether the criticism is valid at high proportions of right turning vehicles. Unfortunately, the data on which the Road Research Laboratory conclusions are based are no longer available, and so the observed turning proportions are unknown. The opposing flows observed are also unknown, and so further comparisons are rather fruitless. In his letter, Dr. Webster agrees, however, that the right turning vehicle factor

'undoubtedly varies with degree of saturation,
width and number of lanes, length of green
period, and opposing flow,'

and that

'our (i.e. the Road Research Laboratory's) result
is an average value covering many dif-
ferent circumstances.'

It is the author's contention that this 'average value' should be set higher than 1.75, or, better still, should be directly linked to the opposing flow. It is also contended that the results of this simulation work, as shown in

figs. 2.25 - 2.30, forms a more reasonable basis for traffic signal design than the use of the global figure of 1.75.

CHAPTER 2 : REFERENCES

- 2.1 D.S.I.R., ROAD RESEARCH LABORATORY, Research on Road Traffic, HMSO, London, 1965.
- 2.2 WEBSTER, F.V., Traffic Signals, DSIR Road Research Lab. Research Note RN/3180/FVW, Feb. 1958 (unpublished)
- 2.3 WEBSTER, F.V., & B.M. COBBE, Traffic Signals, MOT RRL Road Research Technical Paper No. 56, HMSO, London, 1966.
- 2.4 CHARLESWORTH, G., & F.V. WEBSTER, Some Factors affecting the Capacity of Intersections controlled by Traffic Signals, Proc. 4th. Internat. Study Week in Traff. Engng., Copenhagen, 1958.
- 2.5 WEBSTER, F.V., & J.G. WARDROP, Capacity of Urban Intersections, Proc. 6th. Internat. Study Week in Traff. Engng., Salzburg, 1962.
- 2.6 WEBSTER, F.V., Traffic Signal Settings, DSIR Road Research Lab. Tech. Paper No. 39, HMSO, London, 1958.
- 2.7 DSIR ROAD RESEARCH LABORATORY, A Method of Measuring Saturation Flow at Traffic Signals, Road Note 34, HMSO, London, 1963.
- 2.8 MINISTRY OF TRANSPORT, Roads in Urban Areas, HMSO, London, 1966.
- 2.9 MINISTRY OF TRANSPORT, Advisory Memorandum on Urban Traffic Techniques, HMSO, London, 1965.
- 2.10 WEBSTER, F.V., Effect of Right Turning Vehicles at Traffic Signals, MOT Road Res. Lab. Report LR86, Crowthorne, 1968.

- 2.11 ARCHER, R.J.G., R.I. HALL & S. EILON, Effect of Turning Vehicles on Traffic Flow through a Signal Controlled Junction, *Traff. Engng. & Control*, 5(5), Sep. 1963, 295-297.
- 2.12 HIGHWAY RESEARCH BOARD, Highway Capacity Manual, U.S. Govt. Printing Office, Wash., 1950.
- 2.13 HIGHWAY RESEARCH BOARD, Highway Capacity Manual 1965, Special Report 87, Publication 1328, Nat. Academy of Sciences, Was., 1965.
- 2.14 PRETTY, R.L., The Effect of Right Turning Vehicles on Saturation Flow through Signalised Intersections, *Proc. Third Conf. Australian Road Research Board*, Sydney, 1966, 460-470.
- 2.15 LEONG, H.J.W., Some Aspects of Urban Intersection Capacity, *Proc. Second. Conf. Aus. Rd. Res. Bd.*, 2 (1), Sydney, 1964, 305-
- 2.16 GORDON, I.D., & A.J. MILLER, Right Turn Movements at Signalised Intersections, *Proc. Third Conf. Aus. Rd. Res. Bd.*, 3 (1), Sydney, 1966, 446-459.
- 2.17 de MARE, E., Photography, Penguin Books, London, 1959.
- 2.18 GREEN, D.H., Simulation of Merging Streams at an Uncontrolled Intersection, *Dept. Elect. Engng., Manchester Coll. Sc. Tech., Univ. Manchester*, 1965 (unpublished).
- 2.19 RAFF, M.S., & J.W. HART, A Volume Warrant for Urban Stop Signs, Eno Foundation, 1950.
- 2.20 GREENSHIELDS, B.D., D. SCHAPIRO & E.L. ERICKSEN, Traffic Performance at Urban Street Intersections, *Tech. Rep. No. 1.*, Yale Bureau of Highway Traffic, 1947.

- 2.21 BLUNDEN, W.R., C.M. CLISSOLD & R.B. FISHER,
Distribution of Acceptance Gaps for Crossing &
Turning Manoeuvres, Proc. First Conf. Australian
Rd. Res. Bd., 1 (1), Melbourne, 1962, 188-205.
- 2.22 GOURLAY, S.M., Merging Traffic Characteristics Applied
to Acceleration Lane Design, Studies of Weaving &
Merging Traffic, Tech. Rep. No. 4, Yale Bureau
of Highw. Traff., 1948, 61-77.
- 2.23 STRICKLAND, R.I., A Study of Merging Vehicular Traffic
Movements, Studies of Weaving & Merging Traffic,
Tech. Rep. No. 4, Yale Bureau of Highw. Traff.,
1948, 81-101.
- 2.24 BISSELL, H.H., Traffic Gap Acceptance from a Stop Sign,
Univ. of Calif. Inst. Transpn. & Traff. Engng.,
unpublished grad. res. rept., Berkeley, 1960.
- 2.25 SOLBERG, P., & J.C. OPENLANDER, Lag & Gap
Acceptances at Stop-Controlled Intersections,
Highw. Res. Rec. No. 118, Wash., 1966, 48-67.
- 2.26 FINNEY, D.J., Probit Analysis - A Statistical Treatment
of the Sigmoid Response Curve, 2nd Ed., Cambridge
Univ. Press, Cambridge, 1962.
- 2.27 PARADINE, C.G., & B.H.P. RIVETT, Statistical Methods
for Technologists, 2nd Ed., English Univ. Press,
London, 1960.
- 2.28 FISHER, R.A., & F. YATES, Statistical Tables for Biological,
Agricultural & Medical Research, 6th Ed., Oliver &
Boyd, London, 1963.
- 2.29 WAGNER, F.A. Jr., An Evaluation of Fundamental Driver
Decisions & Reactions at an Intersection, Highw.
Res. Rec. No. 118, Wash., 1966, 68-84.

- 2.30 RORBECH, J., Critical Lag in At-Grade Intersections,
Traff. Engng. & Control, 8 (8), Dec. 1966, 500-501.
- 2.31 ASHWORTH, R., & B.D. GREEN, Gap Acceptance at an
Uncontrolled Intersection, Traff. Engng. & Control,
7 (11), Mar. 1966, 676-678.
- 2.32 DREW, D.R., Gap Acceptance Characteristics for Ramp-
Freeway Surveillance & Control, Highw. Res. Rec.
No. 157, Wash., 1967, 108-143.
- 2.33 WORRALL, R.D., D.W. COUTTS, H. ECHTERHOFF-
HAMMERSCHMID & D.S. BERRY, Merging Behaviour
at Freeway Entrance Ramps: Some Elementary
Empirical Considerations, Highw. Res. Rec. No. 157
Wash., 1967, 77-107.
- 2.34 HARMELINK, M.D., Volume Warrants for Left Turn Lanes
at Unsignalised Grade Intersections, Ontario Dept.
Highway Rep. No. RR 122, Out., 1967.
- 2.35 BUHR, J.H., Gap Stability & Its Application to Freeway
Merging Control Systems, Traff. Engng., 38, Mar.
1968, 34-44, 47, 53.
- 2.36 SALTER, R.J., Capacity of Priority Intersections, Traff.
Engng. & Control, 10 (3), Jul. 1968, 134-136, 140.
- 2.37 CHARLESWORTH, G., & J.C. TANNER, Road Junctions
in Rural Areas, DSIR Road Res. Paper No. 47,
HMSO, London, 1960.
- 2.38 BENBOW, C.R., Investigation of Delays at an Uncontrolled
Intersection, DSIR Road Res. Lab. Note No. LN/
184/CRB, Oct. 1962 (unpub.).
- 2.39 YOUNG, A.P., A Study of Weaving Sections, Unpub.
dissert. for Dipl. Traff. Engng., Dept. Civil Engng.,
Univ. Newcastle upon Tyne, 1965.

- 2.40 TING, S.M., A Study of Minimum Gap Acceptance & its Application to Traffic Simulation for Uncontrolled Intersections, unpub. thesis sub. for MSc., Dept. Civil Engng., Univ. Sheffield, 1968.
- 2.41 ASHWORTH, R., A Note on the Selection of Gap Acceptance Criteria for Traffic Simulation Studies, Transpn. Res., 2 (2), Jun. 1968, 171-175.
- 2.42 ADAMS, W.F., Road Traffic Considered as a Random Series, Jour. Instn. Civ. Engrs., 4, Nov 1936, 121-130.
- 2.43 GERLOUGH, D.L., Use of Poisson Distribution in Highway Traffic, Poisson & Traffic, Eno Foundation, Saugatuck, Conn., 1955, 1-58.
- 2.44 GERLOUGH, D.L., Traffic Inputs for Simulation on a Digital Computer, Proc. Highw. Res. Bd., 38, Wash., 1959, 480-487.
- 2.45 SCHUHL, A., The Probability Theory Applied to Distributions of Vehicles on Two-Lane Highways, Poisson & Traffic, Eno Foundation, Saugatuck, Conn., 1955, 59-75.
- 2.46 BUCKLEY, D.J., Road Traffic Headway Distributions, Proc. First Conf. Australian Road Res. Bd., 1 (1), Melbourne, 1962, 153-187.
- 2.47 NEWELL, G.F., Statistical Analysis of Flow of Highway Traffic through a Signalised Intersection, Appl. Math. 13 (4), 1956.
- 2.48 WEBSTER, F.V., Experiment on Saturation Flow or right-turning vehicles at traffic signals, Traff. Engng. & Control, 6 (7), Nov 1964, 427-430, 434.
- 2.49 Private correspondence with F.V. Webster dated 29 August 1968, & 30 September 1968.

CHAPTER 3: WEAVING SECTION SIMULATION

3.1 DELAY ON WEAVING SECTIONS

A weaving section may be defined as (ref. 3.1)

'A length of one-way roadway serving as an elongated intersection of two one-way roads crossing each other at an acute angle in such a manner that the interference between cross traffic is minimised through substitution of weaving for direct crossing of vehicle pathways'.

Very little has been published on the problem of delay on weaving sections. NORDQVIST (1962, ref. 3.2) in a general paper on the problem of delay at intersections proposed the following model:

$$\bar{d} = 1.8 \left(\frac{1}{1 - u} \right)^{0.83}$$

where \bar{d} is the average delay/veh. and
 u is the degree of saturation (i.e. flow/
maximum possible flow at any particular
traffic distribution).

The data on which he bases the above model are not given in the paper.

WEBSTER et al. (1962, ref. 3.3), reporting on the capacity of urban intersections, found that the practical capacity of a weaving section could be defined by

$$Q_p = 86W (1 + e/W) (1 - p/3) / (1 + W/l)$$

where W = Width of weaving section (ft.)
 e = Average of entry widths (ft.)

W = Length of weaving section (ft.)

p = Proportion of weaving traffic

Q_p = Practical capacity (pcu/h).

(The work was based upon tests at Northolt Airport which are reported in ref. 3.4). The parameters used in the above formula should be within the ranges:

W	:	20-60
e/W	:	0.4-1.0
W/l	:	0.12-0.4
p	:	0.4-1.0

An example of the effect of increase in flow on delay for one particular roundabout was shown in the paper, and this example is reproduced as fig. 3.1.

Work at the Road Research Laboratory (ref. 3.5) has indicated that the delay at roundabouts may be split into two components

- i) 'The delay caused by slowing down, travelling the extra distance round the roundabout and accelerating to the normal speed of the road', and
- ii) 'Delay caused by queueing to get into the roundabout and by obstruction by other vehicles while in the roundabout.'

Component (i) has been tabulated (Table 9.9, ref. 3.5) for various road speeds, radii of curvature and negotiating speeds assuming decelerations and accelerations of 0.2g and 0.15g respectively. Observations at six roundabouts were used to obtain data on component (ii), the mean effect being shown as a curve which is reproduced as fig. 3.2. The effect of locking (illustrated in fig. 3.1) was ignored.

Possible capacities of weaving sections in American conditions have been

investigated in some detail in Chapter VII of ref. 3.6, but no method has been described for the prediction of delays to weaving traffic. The American approach to weaving section capacity differs from the British in that the former uses the width described as an integer number of lanes: the Road Research Laboratory method uses widths expressed in feet for predicting capacity.

3.2 CAR FOLLOWING THEORY

Before constructing a simulation model to simulate a long weaving section, it was considered necessary to describe the motion of individual vehicles within the system. Car following theory provides such a method. The basic assumption of the car following theory of traffic flow along a single lane of a highway is that each vehicle in the line of traffic follows the one in front of it according to some stimulus - response law which may be expressed in the form

$$\text{Response} = \text{Sensitivity} \times \text{Stimulus}.$$

- i) Response. This is usually assumed to be the acceleration or deceleration of the vehicle after a certain driver/vehicle reaction time, and is the only variable directly in the control of the driver.
- ii) Stimulus. Usually assumed to be the relative velocity of the leading and following vehicles.
- iii) Sensitivity. Various forms of sensitivity have been proposed, and they are described below.

3.2.1 Constant Sensitivity

Historically, the first model to be considered was one in which the sensitivity was assumed to be constant (refs. 3.7 and 3.8). Experiments were carried out at the General Motors test track with a pair of vehicles. The spacing between the vehicles was monitored by a device incorporating a length of wire, one end of which was attached to the leading vehicle. The other end of the wire was wound onto a drum attached to the following vehicle, and a torque was applied to the drum which kept the wire taut. Changes in spacing were observed by measuring the movements of the drum.

The stimulus was found to be primarily the relative speed of the two vehicles, and the model

$$\ddot{x}_{n+1}(t+T) = \lambda (\dot{x}_n(t) - \dot{x}_{n+1}(t))$$

was proposed,

where $\ddot{x}_{n+1}(t+T)$ is the acceleration of the following vehicle at time $t+T$,

t is any time,

T is the reaction time of the following vehicle and driver,

λ is the sensitivity (a constant)

$\dot{x}_n(t)$ is the speed of the leading car at time t , and

$\dot{x}_{n+1}(t)$ is the speed of the following car at time t .

Average values of λ and T were found to be 0.368 and 1.55s, respectively, by using linear regression techniques on the experimental data.

3.2.2 Step Function

HERMAN et. al. (1959, ref. 3.9) proposed a step function for λ , the sensitivity

$$\lambda(p) = a \text{ if } 0 < p < p_1$$

$$B \text{ if } p > p_1$$

where a and B are constants, p is $x_n - x_{n+1}$ and p_1 is a critical value of p . This model allows for the spacing of the two vehicles to be taken into account, and could describe, in the extreme, the more violent panic reaction of a following driver close to the lead vehicle by making $B \gg a$.

3.2.3 Reciprocal Spacing

The step function sensitivity led GAZIS et al. (1959, ref. 3.10) to the development of the reciprocal spacing sensitivity:-

$$\lambda = \alpha_o / (x_n - x_{n+1})$$

where α_o is constant. Since α_o has the dimensions of speed, α_o was named the Characteristic Speed. This particular model gave extremely good correlations (0.97) with observed performance. The authors demonstrated (ref. 3.10) that the model could be used to develop GREENBERG's (1959, ref. 3.11) traffic equation of state:

$$q = ck \log (k_i/k)$$

where q is the flow,
 c is the optimum speed when q is the maximum
 k is the concentration
 k_i is the concentration in jam conditions

by equating α_o to c . They verified their work by measuring c and α_o in the Lincoln, Holland and Queens Mid-Town Tunnels by consideration of the stream as a whole and by consideration of a pair of vehicles only. Close agreement was noted.

3.2.4 Visual Angle Models

Both PIPES (1967, ref. 3.12) and LEE et al. (1967, ref. 3.13) have suggested that the rate of change of the visual angle should be used as the stimulus. (The visual angle is the angle subtended at the eye by the leading vehicle.) In all practical cases, this reduces to a sensitivity of the form

$$\gamma / (x_n - x_{n+1})^2$$

where γ is constant, and relative speed is the stimulus. Close agreement to observed conditions was reported by Lee (ref. 3.13).

3.2.5 The Model Adopted

The success of the work by Gazis (ref. 3.10) and further work by CONSTANTINE (1967, ref. 3.14) using a photographic technique to collect field data led to the adoption of the Reciprocal Spacing car following model for the weaving section simulation. On the basis of data published so far, the model gives the best fit to observed field data in both U.K. and U.S.A. conditions. This fact, combined with the agreement with Greenberg's equation of state, referred to in Section 3.2.3, made the model the obvious choice.

3.2.6 Restrictions

A car following model cannot be used for simulation work without some reservations. The first is that realistic estimates of the characteristic speed and driver reaction time must be made. Those used in this work were based upon observations made by the authors of ref. 3.14 in Sheffield in 1967 (unpublished). Thirteen drivers were observed using the photographic technique described in ref. 3.14 for a total time of 8 minutes. Subsequent analysis showed that the reciprocal spacing model gave the best fit to the observed data, and that the average characteristic speed was 18.18 ft./s and the average driver reaction time was 0.70s. Herman's work (ref. 3.9) in tunnels produced values of 29.3 ft/s and 1.1s, respectively. The Sheffield observations were made in a busy shopping area on a two lane dual carriageway - very different conditions from those observed by Herman - and so they cannot be expected to produce results very close to Herman's work. The Sheffield results are presumably representative of British conditions, and they were therefore used as a starting point in the simulation.

When used with a constant scanning interval, the car following model can produce extremely violent accelerations in the following vehicle - accelerations

and decelerations which would be impossible for an actual vehicle to produce. The extent of this effect depends upon the length of the scanning interval chosen, and the longer the scanning interval, the more violent the accelerations. The effect is produced because, in real life, a driver is continually assessing his driving situation and making adjustments to the velocity of his vehicle - i.e. he uses an infinitely short scanning interval. In the simulation the situation is only corrected at each scan interval and situations which in real life would be corrected immediately are maintained over the scanning interval. The difficulty may be overcome by using a very short scanning interval, which is wasteful of computer time, or by imposing limits upon the accelerations and decelerations which may be produced in the model. The latter was used in this work.

The distance between pairs of vehicles over which car following conditions may be said to apply is uncertain. Herman (ref. 3.9) postulates a maximum distance of 200 ft. which is based upon consideration of correlation with observed data. Other authors have postulated other figures based upon time headways, e.g. U.S. Highway Capacity Manual (1950, ref. 3.15) gives 9s (this represents a distance of 396 ft. at 30 mile/h), GEORGE (1955, ref. 3.16) gives 6s (264 ft.), and EDIE et al. (1958, ref. 3.17) gives 11s (484 ft.). PIPES (ref. 3.12) gives a distance of 380 ft., a value which is based upon a visual angle car following model, a relative speed of 10 mile/h, and consideration of the threshold of perception of the rate of change of visual angle work by MICHAELS et al. (1963, ref. 3.18). LEE et al. (ref. 3.13) give a figure of 50m for a relative speed of 1 m/s, basing their work on Pipe's principles. In this simulation the maximum separation over which car following conditions may be said to apply was considered to be unimportant, because gaps of such length rarely occur in heavy traffic, and the distances postulated were, in any case, of the same order of magnitude of the length of most weaving sections.

3.3 WEAVING

The lane changing, or weaving, manoeuvre has received remarkably little attention from investigators in the past. WYNN (1948, ref. 3.19) used a photographic technique to obtain data on 193 weaving manoeuvres on a 1,000 ft. section of expressway. He classified the manoeuvres by using a complex classification system, and studied lateral and longitudinal movements, times, speed differentials and gap lengths for each class of manoeuvre. Of particular interest is the 'gap weave' manoeuvre where the weaving vehicle moves into a gap in the receiving stream. Where the manoeuvre was 'optional' (i.e., not imposed by physical or traffic conditions), Wynn found the average length of the receiving gap to be 3.7s. Where 'forced' (e.g. by a parked car in the weaving vehicle's stream) he found the average length of the receiving gap to be 3.0s, ranging between 2 and 4s.

KNOX (1964, ref. 3.20) used a similar technique in a study in Sydney, Australia. He used the A.A.S.H.O. definitions (ref. 3.21) to make a distinction between 'merging' and 'weaving', viz:

- merging : the converging of separate streams of traffic into a single stream;
- weaving : the crossing of traffic streams moving in the same general direction accomplished by merging and diverging.

The study was accordingly split into two phases: a weaving study and a merging study. For the weaving study a 440 ft. long weaving section four 12 ft. lanes wide was chosen. 154 weaving movements were studied, and the relationship between length of weave and speed investigated using linear regression techniques.

The merging study took place at a 500 ft. long section of expressway, where the width at entry was 36 ft. (three lanes), and 24 ft. (two lanes) at exit. Observations and conclusions were based upon 31 min. filming of average flow rates of 1580 veh/h/lane. Regression lines of length of weave v. speed of merging vehicle were plotted. The sizes of gaps accepted by

merging vehicles at various merging speeds were plotted together with safe merging gaps predicted by the work of HAIGHT et al. (1962, ref. 3.22) using parameters appropriate to Australian conditions. The acceptable merging gaps observed ranged from 1.5s to 4s and agreed well with the results predicted by Haight's theory.

Haight computed safe following headways and thence safe merging gaps theoretically by considering vehicle performance and driver reaction time. He assumed that average maximum and minimum acceleration rates were always employed, whatever the manoeuvre, and that all drivers have the same acceleration characteristics. He concluded that

$$y = V_2 T + \frac{V_2^2 - V_1^2}{2a}$$

where y = spacing between leading and trailing vehicle

V_1 = speed of leading vehicle

V_2 = speed of trailing vehicle

a = average maximum braking deceleration

T = reaction time of trailing driver.

The safe following distance y_0 was defined to be a distance large enough for the trailing vehicle to come to a safe stop should the leading vehicle make an emergency stop. (When $V_2 = V_1$, the above equation reduces to

$$y = V \cdot T)$$

The safe merging gap was computed by using the fact that the safe following distance y was required in front of, and behind, the merging vehicle, therefore

$$S = y_1 + y_2 + L$$

where S = safe merging gap (i.e. distance)

L = length of the merging car.

3.4 THE MODEL

The arrangement of the modelled weaving section is shown in fig. 3.3. It was intended to model a long weaving section as may be found at urban motorway junctions, rather than the short weaving sections commonly found in roundabouts in this country at present. The distinction is made because the situation at short weaving sections is usually a gap acceptance situation where entering vehicles stop and move through a gap in the conflicting stream. It was desired to simulate a long weaving section where the weaving vehicle moves along the section whilst awaiting a weaving opportunity, adjusting its speed to that of the conflicting stream, so as to bring itself adjacent to a suitable gap. It is acknowledged that this true weaving situation occurs but rarely in this country at present, owing to both bad design and driving behaviour. However, with the onset of increased congestion and the construction of better road facilities, it is expected that 'true' weaving will occur more frequently. It is hoped that this model will provide a useful analysis tool in the future. (The simulation of the 'gap acceptance' situation at short weaving sections has been described in refs. 1.4, 1.6, and 2.40).

The arrangement of the program is shown in fig. 3.4. Segments 1 - 7 and 15 are concerned with the mechanics of the program, and segments 8 - 14 contain the traffic logic. Segments 8 - 14 are described in detail below.

3.4.1 Scanning Technique (Segment 8)

A constant scanning interval was used in this model, as in the traffic signals model, for the reasons described in Section 1.2.1. It was necessary to fix this scanning interval at the same value as the driver reaction time because of the use of car following theory. As explained in Section 3.2.3, car following theory makes use of data at any time t and uses it to predict the acceleration at time $t + T$, where T is the driver reaction time. Therefore in the model, accelerations computed at scan N are applied at scan

$N + 1$, and the time difference between consecutive scans is necessarily equal to the driver reaction time. (In practice each driver would have his own individual reaction time. An average value is used in the model and applied to each vehicle.)

3.4.2 Congestion (Segment 9)

When either or both lanes are full of queueing traffic the run is stopped and an appropriate warning output. The length of the queue is calculated by multiplying the number of queueing vehicles by the vehicle length, and the queue length is then compared with the length of the weaving section. (The vehicle length is the same for each vehicle.) This part of the program is shown in flow diagram form in fig. 3.5. (For convenience, the 'diamond' shaped box convention has been abandoned in this and the following flow diagrams.) If either lane is congested, the simulation is abandoned for the particular set of conditions and the next run commenced. If no further simulation runs are required, the program stops.

3.4.3 Updating (Segment 10)

This part of the program is explained in flow diagram form on fig. 3.6. Each lane is dealt with in turn, the right hand lane first. The first non-queueing vehicle in the lane is found (i.e. the nonqueueing vehicle nearest the exit), and its current speed calculated from its speed at the previous scan, and the acceleration of the vehicle computed from conditions at the previous scan. If this new current speed is less than 5 ft./s, then the vehicle's current speed is set to 5 ft./s, in order to simulate a slow moving vehicle joining the queue or arriving at the exit, still awaiting a weaving opportunity. If the vehicle's new current speed is greater than its entry speed, its current speed is set to the vehicle's entry speed.

The vehicle's current position is calculated next by multiplying the vehicle's current speed by the scanning interval and adding this distance to the vehicle's position at the previous scan. If this new vehicle position is closer to the

exit than the end of the queue, the vehicle is added to the queue, its speed is set to zero and its position set to that of the last vehicle in the queue. If no queue is present, two cases arise. If the vehicle is one which requires to weave but has not yet done so, and it has arrived at the exit, it forms the first vehicle of a queue at the end of the section. If it has weaved, or did not require to do so, it is discharged from the system. The delay to the vehicle is computed at its discharge by subtracting the time that would have been taken by the vehicle proceeding through the section at its entry speed from the actual time taken.

The above is repeated for each non-queueing vehicle in the right hand lane, and then for each non-queueing vehicle in the left hand lane.

3.4.4 Vehicle Generation (Segment 11)

Vehicles are generated by random sampling from a shifted exponential distribution of arrival gaps. Separate, distinct, distributions are used for each lane. Arrival gaps are added to a 'gap store', and one scan interval is subtracted from the gap store at each scanning interval. On entry to Segment 11, the gap store appropriate to the lane under consideration is inspected. If the gap store is equal or less than zero, a vehicle is deemed to have arrived. If there is room for the vehicle to enter the section, i.e. if the rear end of the last vehicle generated has passed the section entrance, the vehicle is generated. If there is no room for the new vehicle to enter, the program moves on to Segment 12, leaving the gap store unchanged. When the segment is re-entered at the next scan, the gap store will be at its former value, minus one scan interval, i.e. still negative, and the situation is re-examined to see if there is now room for the vehicle to enter the section. The form of the gap distribution is only locally distorted by this mechanism because when the vehicle eventually enters the section, a new gap is generated which is added into the gap store: the new gap does not replace the value in the store. e.g., If a vehicle has been stored for three scan intervals before it enters the section, when it finally enters the section the value in the gap store will be -3 scan intervals. On entry,

a new gap is generated - say of 7 scan intervals duration - and added into the gap store. The new value in the gap store will be $-3 + 7 = +4$ scan intervals, i.e. the next vehicle will be generated in 4 scan intervals, not 7.

With the generation of the new vehicle, various items of information are stored:

- i) The elapsed time since the start of the simulation. This is the vehicle's 'arrival time', and remains constant.
- ii) The vehicle's required turning movement is generated by random sampling from a rectangular distribution. This item is changed only when a weaving vehicle has completed its manoeuvre.
- iii) An entry speed is generated from an approximately normal speed distribution. This is the vehicle's 'desired speed' and remains constant.

The speed generation method is that described in Section 1.3.5 which was used by Francis (ref. 1, 42) in his work on the simulation of networks for area control investigations. A fuller discussion of the method is given in Appendix VI.

- iv) The vehicle's 'current speed' is set equal to its entry speed and stored until it is changed in segment 10 at the next scan.
- v) The vehicle's position is set to zero and stored until it is changed in Segment 10 at the next scan (position is measured as the distance from the entry point in feet).

- vi) The current acceleration is set at zero and stored until it is changed in Segment 14 later on in this scan. Accelerations are measured in ft./s^2 .

Different turning proportions and entry speed distribution are used for each lane. The parameters describing these distributions are input as data at the beginning of the program.

3.4.5 Queue Clearance (Segment 12)

Queues are formed initially by vehicles arriving at the end of the section before they have been able to weave. Once the queue has been started, other vehicles in the lane are blocked whether they are weaving vehicles or not. A queue of vehicles cannot discharge any faster than about 1960 veh/h per 12 ft. lane (ref. 2.3), which is about 1.85s/veh. Since it was expected that a scanning interval of about 1s would be used, it was impossible to allow one vehicle to discharge from the front of the queue in each scan interval, because this would simulate extremely high saturation flow rates of the order of 3600 veh/h. It would have been possible to simulate a specified saturation flow, as in the traffic signals program, by subtracting a fraction of a vehicle from the queue at each scan interval. However, it was considered that this refinement was a complication to an already large and complex program, and a coarser method of producing reasonable saturation flow rates was employed. Vehicles were subtracted from the queues at every other scan interval. The saturation flow rate was then equal to

$$3600 / (2 \times t)$$

where t is the scan interval in seconds. Use of a scan interval of approximately 1s would therefore simulate a queue clearance rate of approximately 1800 veh/h - a more appropriate value than 3600 veh/h. This mechanism, then, explains the significance of the second question on fig. 3.8.

The logic of the lane-changing decision is shown on fig. 3.9. Observations

to date have measured acceptable gaps in traffic streams in time only, and this method may be acceptable at a freeway on-ramp where conditions remain stable and priority is clearly defined. Several difficulties arise when simulating a lane change decision, however. In a weaving section, the size of any gap is not likely to remain constant for very long. This raises the problem of whether the weaving driver assesses the gap size and bases his decision on that size, or whether he assesses what the gap size will be when he has completed his manoeuvre and bases his decision on this estimated gap size. Also the data published by Wynn and Knox takes very little account of the relative speed of the vehicle opening the gap, the vehicle requiring to weave, and the vehicle closing the gap. Intuitively one would expect the minimum acceptable time gap to increase in length as the relative speeds of the three vehicles increased. Knox attempted to overcome this deficiency by applying Haight's theory to his observations, but the fit was not particularly good. Haight's theory, in any case, is based upon the assumption that no weaving vehicle would accept a gap that would result in the trailing vehicle decelerating. This assumption is probably valid at an on-ramp situation, for which the theory was developed, where priority is clearly with the main stream. This simulation model is, however, designed to simulate urban weaving sections. Under heavy traffic conditions the vehicle closing the gap must, in the author's opinion, be prepared to accommodate the weaving vehicle by decelerating to a certain extent. In congested urban traffic there are, presumably, certain acceptable acceleration and decelerations which drivers are prepared to apply to their vehicles in order to accommodate other drivers. On this assumption, then, the mechanism simulating a lane change decision was based. The decision mechanism is shown as a flow diagram in fig. 3.9, and the non-queueing situation as the top diagram in fig. 3.10. (The non-queueing situation is examined in segment 13 - it is explained at this point in order to make the queue clearance situation clearer.) The vehicles in the lane opposite the weaving vehicle immediately in front or behind are found. (Vehicles A and B in fig. 3.10.) The positions of the three relevant vehicles are examined to find, first of all, whether the weaving vehicle has the

physical room to change lanes. If it has, the vehicle is imagined to have weaved, and the accelerations of the weaving vehicle and the vehicle behind it are examined. If either of these accelerations exceed specified positive or negative limits, the vehicle is judged not to have weaved, and the program moves on. If conditions are acceptable for the vehicle to weave, it is moved over instantaneously. In fact, of course, the lane changing manoeuvre takes a finite time to accomplish, and Knox observed the times to range from 5.7 - 9.3s. However, it was considered that little improvement in accuracy would have been gained in simulating this time within the model and it was ignored.

From the top diagram in fig. 3.10, at any time t let:-

d_a be the position of vehicle A,

d_B be the position of vehicle B,

d_W be the position of vehicle W,

v_A be the speed of vehicle A,

v_B be the speed of vehicle B,

v_W be the speed of vehicle W,

and assume that vehicles A, B and W are all of the same length L .

Let S_{AW} be the spacing between vehicles A and W.

Then
$$S_{AW} = d_A - d_W - L$$

Let S_{WB} be the spacing between vehicles W and B

$$S_{WB} = d_W - d_B - L$$

Suppose vehicle W changes lanes instantaneously. Assuming V_A and V_B

and V_W to remain constant, and T to be the driver reaction time (supposed constant for all drivers), from the Reciprocal Spacing Car Following Law, at time $(t + T)$:-

$$f_W = a (V_A - V_W) / S_{AW} \dots 3.1$$

$$f_B = a (V_W - V_B) / S_{WB} \dots 3.2$$

where f_W and f_B are the accelerations of vehicles W and B respectively.

The time headway between vehicles A and B, h_{AB} , is

$$\begin{aligned} h_{AB} &= (d_A - d_B) / V_B \\ &= (2L + S_{AW} + S_{WB}) / V_B \dots\dots 3.3 \end{aligned}$$

Substituting in equ. 3.3 for S_{AW} and S_{WB} from equs. 3.1 and 3.2, we have:-

$$h_{AB} = \frac{1}{V_B} \left(2L + a \frac{(V_A - V_W)}{f_W} + a \frac{(V_W - V_B)}{f_B} \right)$$

Let the maximum tolerable acceleration be f_{\max} , and the minimum tolerable acceleration (i.e. maximum tolerable deceleration) be f_{\min} , and assume that these limits are the same for all vehicles.

If $V_A = V_B = V$, and $V_W < V$, the minimum value of h_{AB} (h_{\min}) is

$$\begin{aligned} h_{\min} &= (2L + a (V - V_W) / f_{\max} + \\ &a(V_W - V) / f_{\min}) / V \dots\dots\dots 3.4 \end{aligned}$$

If $V_A = V_B = V$, and $V_W = V$, then

$$h_{\min} = (2L + a (V - V_W) / f_{\min} +$$

$$a (V_W - V) / f \max) / V \quad \dots\dots 3.5$$

If $V_A = V_B = V_W = V$, then

$$h \min = 2L/V \quad \dots\dots 3.6$$

The value of $h \min$ predicted by equ. 3.6 is clearly ridiculous. It predicts that, if the speed of the weaving vehicle is equal to the speed of the stream into which it requires to merge, the weaving vehicle merely requires a physical gap long enough to accommodate its own physical length; i.e. after the merge has taken place the three vehicles would be travelling with their bumpers touching one another. Haight's theory for this particular circumstance is more realistic, in that he says that

$$h \min = 2T^1 + L/V$$

where $T^1 =$ minimum following headway.

This fault of the theory developed here (i.e. the fact that no account of the observable minimum headway is taken) is inherent in car following theory, in that when the speed of any two vehicles is equal, no accelerations to the following vehicle result, whatever the current following headway. In practice, of course, even if the speed of a trailing vehicle were equal to the speed of the leading vehicle of a pair of vehicles, the driver of following vehicle would increase his speed until his following headway reached its minimum tolerable value. Current car following theories take no account of this effect. It is suggested that even if the speeds of a pair of vehicles were equal, and if the current following distance was less than the minimum tolerable following distance, the following vehicle would apply a deceleration, i.e.

$$f(t + T) = F(T^1, S, V_r) t$$

where $f(t + T) =$ Acceleration at time $t + T$ where T is the driver reaction time,

- F = Some function
 T^1 = Minimum time headway
 s = Spacing
 V^r = Relative speed of the two vehicles
 t = Any time.

It is also suggested that the reverse is true: i.e. that if the speed of the two vehicles is equal but the following distance is greater than the minimum tolerable, the following vehicle will increase its speed until the following distance is at its minimum value. Unfortunately it is beyond the scope of this work to investigate these suggestions any further, and existing car following theory was used in the model despite its shortcomings. It is not anticipated that any significant inaccuracies resulted because, under heavy traffic conditions, the vehicles entered the system at time headways close to the minimum in any case. Under lighter traffic conditions it is possible that some inaccuracy developed: precisely how much is difficult to estimate. Since delay was the quantity under examination in the work, however, and the largest delays were incurred under heavy traffic conditions, any inaccuracies occurring under light traffic conditions have been assumed to be negligible.

Application of the above theory requires knowledge of the range of tolerable accelerations and decelerations acceptable to drivers in urban conditions: accordingly apparatus was designed to collect suitable data and it is described in Section 4.5. The results of the collected data are analysed and presented in Section 3.7.1.3.

Several situations occur in the queue clearance situation. A priority rule from the right is observed, i.e., if vehicles are present in both queues, the first vehicle in the right hand lane queue changes lanes and is discharged (see centre diagram, fig. 3.10). Each vehicle down the right hand lane queue is then examined for a desire to weave. If a space in the opposite queue is available ahead of the vehicle requiring to weave, and the manoeuvre would not cause the first non-queueing vehicle (vehicle B) in the opposite lane to decelerate too sharply (see lower diagram, fig. 3.10),

the vehicle W changes lane. Similar reasoning applies if no queue is present in the left hand lane.

The left hand lane queue is then examined and again similar reasoning applies. When all queueing vehicles have been dealt with, the program moves on to vehicles beyond the ends of the queues (segment 15). Figures 3.8 and 3.11 - 18 show flow diagrams which deal with the various queueing situations that arise. Fig. 3.13 requires some explanation. At the box marked '*' the situation occurs where the first vehicle in the left hand lane queue does not require to weave. If this is the case, the vehicle cannot be discharged because a weaving vehicle from the right hand lane queue is crossing in front of it. The decision marked ** includes an investigation as to whether a space is available in the opposite lane in front of the weaving vehicle (see lower diagram in fig. 3.10). If no such space is available, the vehicle requiring to weave cannot do so.

3.4.6 Weaving Vehicles (Segment 13)

The logic dealing with vehicles beyond the end of the queues is shown as a flow diagram on fig. 3.19. The first vehicle in the right hand lane is examined first, and it changes lanes if it desires to so do and if it is safe to so do according to the logic detailed in fig. 3.9. Then the first vehicle in the left hand lane is examined, then the second vehicle in the right hand lane, and so on. The vehicles in each lane are examined concurrently rather than consecutively to avoid the possibility of giving one particular lane precedence over the other. (However, in the queueing situation the right hand lane does have preference - see Section 3.4.5.) Vehicles are not examined by this part of the program unless they are completely within the section. (This is the significance of the fourth box down in fig. 3.19.)

3.4.7 Acceleration Calculations

As explained in Section 3.2.5, the acceleration of each vehicle is calculated by the reciprocal spacing car following law, which states:

$$\ddot{x}_{n+1}(t+T) = a \frac{(\dot{x}_n - \dot{x}_{n+1})}{(x_n - x_{n+1} - L)} \quad (t)$$

i.e., the acceleration of vehicle $n+1$ at time $(t+T)$ is proportional to the relative speed of vehicles n and $n+1$, and inversely proportional to the spacing between them at time t .

Each weaving vehicle in the line is subject to two accelerations: one is the acceleration imposed by the vehicle in front (accrn 20 in fig. 3.21), and the other is caused by the fact that as the vehicle approaches the end of the weaving section it must slow down to a halt if it has not found a weaving opportunity (accrn 1). Both accelerations are calculated for each weaving vehicle, and the lower of the two (i.e. the greater deceleration) is applied to the vehicle. This latter acceleration (accrn 1) is calculated as if the end of the weaving section were a stationary vehicle.

The procedure is as follows. The right hand lane is examined first (see fig. 3.20). The vehicle nearest the exit is found, and if it is a queueing vehicle, it is ignored and the next vehicle is examined. If it is not a queueing vehicle and is not a weaving vehicle, its acceleration is computed as if the end of the weaving section were a vehicle travelling at this vehicle's desired speed. This is to simulate a driver, freed of constraints imposed by a vehicle in front, accelerating to clear the section. If it is a weaving vehicle, the two accelerations mentioned above are calculated (see fig. 3.21) and the lower imposed. Each vehicle is examined in turn in the right hand lane, and then a similar process followed in the left hand lane. If any of the accelerations calculated are higher than the maximum allowed, they are set to this maximum. The accelerations are then stored for use in Segment 10 at the next scanning interval.

3.4.8 Output (Segment 15)

It is possible to output information at any time during the run, and then either return to Segment 8 (fig. 3.4), continuing with the simulation until

the next specified output time; start the next run with fresh input data (Segment 4); or close the program. Two sets of output data are available: the first gives details of the vehicle positions, speeds, turning movements and accelerations, whilst the second gives details of the delays incurred by vehicles travelling on the section. Either or both kinds of output may be specified for each run. A typical sheet of output is shown as fig.

3.22. (Since the size of the program is near the maximum limits that can be handled by the available compilers, the input data is not printed out at the start of each run, as it is in the traffic signals program.)

3.5 THE PROGRAM

3.5.1 Egdon Algol

The program was written in Algol and was intended for use with the Whetstone and Kidsgrove compilers. The program in its complete form proved to be too large for the Kidsgrove compiler to handle, however, and proved to be too slow to run on the Whetstone compiler. In January 1969 the University of Salford Computing Department changed over to the Egdon Operating System (ref. 3.23). Although the Egdon Algol compiler imposes size restrictions, similar to those imposed by the Kidsgrove compiler, the Egdon System has a facility whereby procedures may be separately and independently compiled. Use of this facility enabled the main program and some procedures to be compiled in one run, and other procedures in another. Having compiled the complete program, the system assembles all the necessary procedures by removing them from temporary storage on the disc and transferring them to the corestore of the machine.

3.5.2 Vehicle Storage

Information about the vehicles using the section is stored in two two-dimensional arrays, each 100×6 , and names 'lhveh' (vehicles in the left hand lane) and 'rhveh' (vehicles in the right hand lane). Six items of information are relevant to each vehicle, and each array stores 100 of such sets. For, for instance, vehicle number 58 in the right hand lane,

rhveh (58, 1) contains the time that the vehicle entered the section; rhveh (58, 2) contains a number which indicates the turning movement of the vehicle:

1 indicates that the vehicle requires to weave,
0 indicates a non-weaving vehicle, and 2
indicates that the vehicle has changed lanes;
rhveh (58, 3) stores the entry speed of the
vehicle (all units are in feet and seconds);

rhveh (58, 4) contains the current speed of the vehicle;
rhveh (58, 5) contains the current distance of the vehicle from its entry point;
rhveh (58, 6) contains the acceleration of the vehicle, either the current acceleration or the acceleration of the vehicle at the next scan, depending upon the point in the program.

A circular store is used for each lane, in a similar manner to that used for the right hand lane queue in the traffic signals program (see Section 2.4.3), the only difference being that a 100×6 array is used instead of a 100×1 array. The number of vehicles on the section at any one time is stored in identifiers 'right' and 'left'. Therefore, as a vehicle arrives, 'right' or 'left' is increased by 1, as appropriate. The number of the leading vehicle in each lane is stored in 'headrh' and 'headlh'. As a vehicle leaves the section, 'headrh' or 'headlh' is increased by one, and 'right' or 'left' decreased by one.

3.5.3 Input Data

A 'run' is defined to be a simulation for one set of input data, but it is possible to input several such runs to the computer at any one time. The program will complete the first run and automatically move on to the next. All the data for all the runs is read in at one time, and the tape reader is then closed so that the machine may be used in its time sharing mode.

The data must be input in the order listed below. It is stored until required for each particular run in the array 'data'. The identifier to which the item of data is assigned for each run is given in brackets in the list below. All the units are in feet and seconds.

First, the number of runs required, and then, for each run:

1. The run number ('run'). This number must be an integer.
2. The number of printouts required. ('Print'). This number must be at least 1. Then follows a list of the times required for the printouts. The program will then printout the state of the simulation at these specified times, and will terminate the run at the last time specified. These times are stored in the array 'thyme'. A maximum of 30 printouts is allowed.
3. The scanning interval, and therefore the driver reaction time ('scan').
4. The first random number to be used by the random number generator ('yo'). This number must be an 11 digit, odd number less than 34 359 738 368.
5. The length of the weaving section ('length').
6. The average vehicle length ('carlengt').
7. The characteristic speed for use in the car following formula ('alpha').
8. The average maximum acceleration ('maxaccn').
9. The average maximum deceleration (or average minimum acceleration. It must be expressed as a negative quantity). ('maxdecn').
10. The mean of the speed distribution for the right hand lane ('meanrh').
11. The mean of the speed distribution for the left hand lane ('meanlh').

12. The range of the speed distribution for the right hand lane ('srh').
13. The range of the speed distribution for the left hand lane ('slh').
14. The hourly traffic volume arriving in the right hand lane ('rhvol').
15. The hourly traffic volume arriving in the left hand lane ('lhvol').
16. The minimum arrival gap in the right hand lane ('rhmingap').
17. The minimum arrival gap in the left hand lane ('lhmingap').
18. The proportion of weaving vehicles in the right hand lane ('rhweave').
19. The proportion of weaving vehicles in the left hand lane ('lhweave').
20. A number which should be 1 if a summary of vehicle positions is required at each printout. If this information is not required, any integer number $\neq 1$ should be punched ('posn').
21. A number which should be 1 if a summary of vehicle delays is required at each print out. If this information is not required, any integer number $\neq 1$ should be punched ('delays').

Finally, after all the data for all the runs, the number -1000 should be punched. This enables the program to check that the correct number of items of data, as predicted by the first data item, has been punched and read in. If the data is incorrect, a warning is output and the program stopped.

3.5.4 Text of Program


```

begin integer nnn;
      open(20); open(30);
      writetext(30,[[p]VSO13*41*S.L.SUMNER[c]
        WEAVING*SECTION*SIMULATION*1.9[c]]);
      nnn:=read(20);
begin real
      time,scan,rightgap,leftgap,
      meanrh,meanlh,srh,slh,rhvol,
      lhvol,rhmingap,lhmingap,
      rhweave,lhweave,length,
      alpha,carlengt,maxaccn,
      maxdecn;

      integer
      repeat,k,run,headrh,
      headlh,right,left,y0,
      print,i,rhtally,lhtally,
      rhq,lhq,delays,posn,m,n,o,
      check;

      boolean
      rh,lh,rms,lms;

      real array
      rhveh,lhveh[1:100,1:6],
      delay[1:2,1:2,1:6],
      data[1:nnn,1:51],
      thyme[1:30];

      integer array
      f[1:7],form[1:6];

      real procedure random(a,b,x0);
      value a,b,x0; real a,b; integer x0;
      begin own integer x,m35,m36,m37;
        if x0 $\neq$ 0 then
          begin
            x:=x0;
            m35:= 34 359 738 368;
            m36:= 68 719 476 736;
            m37:=137 438 953 472
          end;

            x:=5*x;
            if x>m37 then x:=x-m37;
            if x>m36 then x:=x-m36;
            if x>m35 then x:=x-m35;
            random:=x/m35*(b-a)+a
          end random;

      real procedure speed(mu,range);
      real mu,range;
      begin real r1,r2,r3,s;
      again:r1:=random(-1.0,+1.0,0);
        r2:=random(-1.0,+1.0,0);
        r3:=random(-1.0,+1.0,0);

```

```

        s:=mu+((r1+r2+r3)/3)*range;
        if s<(mu-range/2) or s>(mu+range/2)
            then goto again;
        speed:=s
    end of speed;

```

```

real procedure fresh(volume,mingap);
real volume,mingap;
begin
    fresh:=mingap-(3600/volume-mingap)
        *ln(random(0,1.0,0))
end of fresh;

```

```

integer procedure look(veh,distance,number,
    head,vehlengt);
integer number,head; real array veh;
real distance,vehlengt;
begin comment Procedure to find the vehicle
    behind a vehicle about to change lane.
    Actual parameters:
    1. Array into which the vehicle
        requires to merge.
    2. Current position of the merging
        vehicle.
    3. The number of vehicles in the
        lane into which the vehicle
        requires to merge.
    4. The number of the lead vehicle
        in the lane into which the veh-
        icle requires to merge.
    5. The average vehicle length;

```

```

integer next;

```

```

next:=head;
if number=0 then
begin
    lok:=1000;
    goto fin
end;

```

```

if distance<(veh[if head+number-1>100
    then head+number-101 else head+number
    -1,5]-vehlengt) then
begin
    look:=1000;
    goto fin
end;

```

```

if (distance-vehlengt)>veh[head,5]
then
begin

```



```

        look:=head;
        goto fin
    end;

    if distance $\geq$ (veh[head,5]-vehlengt)
    then
    begin
        look:=2000;
        goto fin
    end;

pub: if distance<(veh[next,5]-vehlengt)
    then
    begin
        next:=if next=100 then 1 else
            next+1;
        goto pub
    end;

    if (distance-vehlengt)>veh[next,5]
    then
    begin
        look:=next;
        goto fin
    end;

    if (distance-vehlengt)<veh[next,5] or
        distance $\geq$  (veh[next,5]-vehlengt)
    then
    begin
        look:=2000;
        goto fin
    end;

fin:
end of look;

procedure update(veh,number,queue,head,lane,
tally);
integer number,queue,head,lane,tally;
real array veh;
begin comment This procedure moves all
vehicles along that are not in the
queue. If a vehicles speed drops to
below 5 ft/sec, it is held at this
value until the vehicle is forced to a
halt by the end of the queue, or by
the end of the weaving section if it
is a weaving vehicle. Actual para-
meters should appear in the following
order:
    1. Array appropriate to the lane under
        consideration.

```

2. Number of vehicles in this lane.
3. Number of vehicles in the queue.
4. The number of the lead vehicle.
5. 1 for right hand lane, 2 for the left.
6. rhtally or lhtally as appropriate;

integer first,last,t;

if number=0 or queue=number then goto skip;

first:=head+queue;

if first>100 then first:=first-100;

last:=head+number-1;

if last>100 then last:=last-100;

t:=first;

repeat:begin comment Update speed and distance;

veh[t,4]:=veh[t,4]+veh[t,6]*scan;

if veh[t,4]<5 then veh[t,4]:=5;

if veh[t,4]>veh[t,3] then veh[t,4]:=veh[t,3];

veh[t,5]:=veh[t,5]+veh[t,4]*scan;

if queue>0 then

begin

if veh[t,5]>length-queue*carlengt then

begin comment Vehicle joins queue;

veh[t,5]:=length-queue*carlengt;

veh[t,4]:=0;

queue:=queue+1

end;

end

else

begin

if veh[t,2]=1 then

begin

if veh[t,5]>length then

begin comment Weaving vehicle reaches end of section;

veh[t,5]:=length;

queue:=1;

veh[t,4]:=0;

end;

end

else

begin

if veh[t,5]-carlengt>length then

begin comment Non-weaving vehicle is discharged from system;

integer mm;

if veh[t,2]=0 then mm:=1 else mm:=2;


```

if time-(veh[t,1]+(length+carlengt)/
veh[t,3])>scan then
begin
delay[lane,mm,1]:=delay[lane,mm,1]+
(time-veh[t,1])-(length+carlengt)/
veh[t,3]);
delay[lane,mm,2]:=delay[lane,mm,2]+1;
end
else
delay[lane,mm,3]:=delay[lane,mm,3]+1;
tally:=tally+1;
if number≠1 then head:=if head=100
then 1 else head+1;
number:=number-1;
end;
end;
end;

if last>first then
begin
t:=t+1;
if t>last then goto skip else goto
repeat;
end
else
begin
t:=if t=100 then 1 else t+1;
if t>first or t<last then goto repeat
else goto skip;
end;
end;

```

skip:
end of update;

```

procedure laneswap(ex,exhead,exveh,exnumber,
in,inhead,inveh,innumber);
integer in,ex,inhead,exhead,innumber,exnum-
ber;
real array inveh,exveh;

```

```

begin comment Actual parameters (all values
for situation before merging occurs):
For the lane which the vehicle is
leaving,
1. The number of the vehicle.
2. The first vehicle.
3. The array.
4. The number of vehicles on the
section.

```

```

For the lane into which the vehicle
is moving:
5. The vehicle immediately behind
the merging vehicle.
6. The first vehicle.

```

7. The array.
8. The number of vehicles on the section;

```

integer t,u,exlast,inlast;
exlast:=exhead+exnumber-1;
if exlast>100 then exlast:=exlast-100;
inlast:=inhead+innumber-1;
if inlast>100 then inlast:=inlast-100;

exveh[ex,2]:=2;
if innumber<0 then
begin
inhead:=if inhead=100 then 1 else
inhead+1;
for u:=1 step 1 until 6 do inveh[inhead,
u]:=exveh[ex,u];
exnumber:=exnumber-1;
innumber:=1;

if exnumber<0 then
begin
if ex<exhead then
begin
if ex>exlast then
begin
for t:=ex step 1 until 100,1 step 1
until exlast do for u:=1 step 1 until
6 do exveh[t,u]:=exveh[if t=100 then
1 else t+1,u];
end
else
begin
for t:=ex step 1 until exlast do for
u:=1 step 1 until 6 do exveh[t,u]:=
exveh[if t=100 then 1 else t+1,u];
end;
end
else exhead:=if exhead=100 then 1 else
exhead+1;
end;
end
else
begin
if in<1000 then
begin
if in>inlast then
begin
for t:=inlast step -1 until 1,100 step
-1 until in do for u:=1 step 1 until
6 do inveh[if t=100 then 1 else t+1,
u]:=inveh[t,u];
end
else
begin

```



```

for t:=inlast step -1 until in do for
  u:=1 step 1 until 6 do invveh[if t=
    100 then 1 else t+1,u]:=invveh[t,u];
end;
end;

```

```

for u:=1 step 1 until 6 do if in=1000
  then invveh[if inhead+innumber>100
    then inhead+innumber-100 else inhead
    +innumber,u]:=exveh[ex,u] else
    invveh[in,u]:=exveh[ex,u];
innumber:=innumber+1;
if ex≠exhead then
  begin
    if ex>exlast then
      begin
        for t:=ex step 1 until 100,1 step 1
          until inlast do for u:=1 step 1 until
            6 do exveh[t,u]:=exveh[if t=100 then
              1 else t+1,u];
        end
      end
    else
      begin
        for t:=ex step 1 until exlast do for
          u:=1 step 1 until 6 do exveh[t,u]:=
            exveh[if t=100 then 1 else t+1,u];
        end;
      end
    else
      begin
        if exnumber>1 then exhead:=if exhead=
          100 then 1 else exhead+1;
        end;
        exnumber:=exnumber-1;
      end;
    end
  end of laneswap;

```

```

procedure go(lane,turn,head,q,tally,opptally,
  number,veh);

```

```

integer turn,head,q,tally,opptally,number;
real array veh; boolean lane;

```

```

begin comment Procedure to discharge first
  vehicle in queue. Actual parameters
  should be:

```

1. RH for right hand lane, LH for left.
2. 1 for a weaving vehicle, 0 for non-weaving.
3. Number of first vehicle in the queue.
4. Number of vehicles in the queue.
5. Number of vehicles discharged from this lane.
6. Number of vehicles discharged from opposite lane.

7. Number of vehicles in this lane.
8. Array appropriate to this lane;

integer mm,nn;

if lane then rms:=2Xscan else lms:=
2Xscan;

if lane then

begin

if turn≠1 then nn:=1 else nn:=2;

end

else

begin

if turn≠1 then nn:=2 else nn:=1;

end;

if turn=0 then mm:=1 else mm:=2;

delay[nn,mm,1]:=delay[nn,mm,1]+(time
-veh[head,1])-(length+carlengt)/
veh[head,3]);

delay[nn,mm,2]:=delay[nn,mm,2]+1;

q:=q-1;

if turn=1 then opptally:=opptally+1

else tally:=tally+1;

number:=number-1;

if number≠0 then head:=if head=100

then 1 else head+1;

end of go;

boolean procedure loop1(next,veh,oppveh,
number,opnumber,head,opphead);

integer next,number,opnumber,head,opphead;

real array veh,oppveh;

begin comment Procedure to move vehicles;

integer trail;

loop1:=false;

if veh[next,2]≠1 then goto skip;

trail:=look(oppveh,veh[next,5],

opnumber,opphead,carlengt);

if trail=2000 then goto skip;

if trail=1000 then

begin

veh[next,5]:=veh[next,5]+carlengt;

laneswap(next,head,veh,number,trail,

opphead,oppveh,opnumber);

loop1:=true;

end

else

begin real space,accn;

space:=veh[next,5]-carlengt-oppveh
[trail,5];

accn:=if space<0 then veh[next,4]-

oppveh[trail,4] else alphax((veh
[next,4]-oppveh[trail,4])/space);


```

    if accn>maxdecn then
    begin
    veh[next,5]:=veh[next,5]+carlengt;
    laneswap(next,head,veh,number,trail,
    opphead,ppveh,opnumber);
    loop1:=true;
    end;
    end;
skip:
end of loop1;

boolean procedure loop2(next);
integer next;
begin
    loop2:=false;
    if rhveh[next,2]=1 then
    begin
    rhveh[next,5]:=rhveh[next,5]+carlengt;
    laneswap(next,headrh,rhveh,right,1000,
    headlh,lhveh,left);
    loop2:=true;
    end;
end of loop2;

boolean procedure loop3(next,veh,oppveh,
head,opphead,oppq,number,opnumber);
integer next,head,opphead,oppq,number,
opnumber;
real array veh,oppveh;
begin integer place,trail; real accn,spacing;
    loop3:=false;
    if veh[next,2]≠1 then goto skip;
    if next>head then place:=next-head+1
    else place:=(next+100)-head+1;
    if place<oppq+2 then goto skip;
    trail:=look(oppveh,veh[next,5],opnumber,
    opphead,carlengt);
    if trail=2000 then goto skip;
    if trail=1000 then
    begin
    veh[next,5]:=veh[next,5]+carlengt;
    laneswap(next,head,veh,number,trail,
    opphead,oppveh,opnumber);
    loop3:=true;
    end
    else
    begin
    spacing:=veh[next,5]-carlengt-oppveh
    [trail,5];
    accn:=if spacing<0 then veh[next,4]-
    oppveh[trail,4] else alphas((veh[next,
    4]-oppveh[trail,4])/spacing);
    if accn>maxdecn then
    begin
    veh[next,5]:=veh[next,5]+carlengt;

```

```

        laneswap(next,head,veh,number,trail,
            opphead,oppveh,opnumber);
        loop3:=true;
        end;
        end;
skip:
end of lop3;

boolean procedure loop4(next);
integer next;
begin
    lop4:=false;
    if lhveh[next,2]=1 then
        begin
            lhveh[next,5]:=lhveh[next,5]+carlengt;
            laneswap(next,headlh,lhveh,left,1000,
                headrh,rhveh,right);
            loop4:=true;
        end;
    end of loop4;

procedure scramble(veh,oppveh,head,opphead,
    number,opnumber,car,blazes,pot);
real array veh,oppveh;
integer head,opphead,number,opnumber,car;
label blazes,pot;
begin integer follow,precede;
    real accn1,accn2;
    if veh[car,5]<carlengt then goto pot;
    if opnumber=0 then
        begin
            laneswap(car,head,veh,number,1000,
                opphead,oppveh,opnumber);
            goto blazes
        end;
    follow:=look(oppveh,veh[car,5],opnum-
        -ber,opphead,carlengt);
    if follow=2000 then goto blazes;
    if follow=1000 then
        begin comment No vehicle behind
            merging vehicle;
        precede:=if opphead+opnumber-1>100
            then opphead+opnumber-101 else
            opphead+opnumber-1;
        if oppveh[precede,5]-veh[car,5]<
            carlengt then goto blazes;
        accn1:=alphaX((oppveh[precede,4]-veh
            [car,4])/(oppveh[precede,5]-carlengt
            -veh[car,5]));
        if accn1>maxdecn and accn1<maxaccn
            then laneswap(car,head,veh,number,
                follow,opphead,oppveh,opnumber);
        end
        else
        begin
            precede:=if follw=1 then 100 else

```



```

follow-1;
if oppveh

```

```

f[1]:=layout([nddd]);
f[2]:=layout([ssndddd.dd]);
f[3]:=layout([ssd]);
f[4]:=layout([s-ndd.dd]);
f[5]:=layout([s-ndd.dd]);
f[6]:=layout([s-ndddd]);
f[7]:=layout([ssss/ndddd.dd]);

```

```

form[1]:=layout([ndddssddd.dd]);
form[2]:=form[3]:=layout([sndddssddd]);
form[4]:=layout([ndddssddd]);
form[5]:=layout([sssnddd.dd]);
form[6]:=layout([ssssnddd.ddc]);

```

```

rh:=true; lh:=false;
for repeat:=1 step 1 until nnn do
begin integer yy,zz;
for yy:=1,2 do data[repeat,yy]:=read(20);
for zz:=1 step 1 until data[repeat,2] do
data[repeat,2+zz]:=read(20);
for yy:=33 step 1 until 51 do data[repeat,
yy]:=read(20);
end;

```

```

check:=read(20); close(20);
if check≠-1000 then
begin
writetext(30,[[c]error*in*data]);
goto reject
end;

```

```

begin for repeat:=1 step 1 until nnn do
comment Set initial values of variables

```

```

for each run;

run:=data[repeat,1];
print:=data[repeat,2];
for i:=1 step 1 until print do thyme[i]:=
  data[repeat,i+2];
scan:=data[repeat,33];
y0:=data[repeat,34];
length:=data[repeat,35];
carlengt:=data[repeat,36];
alpha:=data[repeat,37];
maxaccn:=data[repeat,38];
maxdecn:=data[repeat,39];
meanrh:=data[repeat,40];
meanlh:=data[repeat,41];
srh:=data[repeat,42];
slh:=data[repeat,43];
rhvol:=data[repeat,44];
lhvol:=data[repeat,45];
rhmingap:=data[repeat,46];
lhmingap:=data[repeat,47];
rhweave:=data[repeat,48];
lhweave:=data[repeat,49];
posn:=data[repeat,50];
delays:=data[repeat,51];

time:=0;
right:=left:=rhtally:=lhtally:=rhq:=lhq:=0;
headrh:=headlh:=0;
k:=0;
lms:=rms:=0;
for n:=1,2 do
  begin
    for m:=1,2 do
      begin
        for o:=1 step 1 until 6 do delay[n,m,o]:=0;
      end;
    end;
    rightgap:=0;      leftgap:=0;
    begin real r;
    r:=random(0,1,y0)
    end;

    write text(30,[[p]run*number]);
    write(30,layout([nddddc]),run);

    if maxdecn>0 then
      begin
        writetext(30,[[***maximum*deceleration
          *should*be*a*negative*quantity*-----
          this*run*is*rejected[cc]]]);
        goto nextrun
      end;
  end;

```


kay: k:=k+1;

start: if time>thyme[k] then goto stop;

if rhq×carlengt>length then goto al3;
if lhq×carlengt>length then goto al4;

time:=time+scan;
if rms>0 then rms:=rms-scan;
if lms>0 then lms:=lms-scan;

if headlh≠0 then update(lhveh,left,lhq,
headlh,2,lhtally);
if headrh≠0 then update(rhveh,right,rhq,
headrh,1,rhtally);

comment VEHICLE ARRIVAL;
if rightgap<0 and (right=0 or rhveh[if
headrh+right-1>100 then headrh+right
-101 else headrh+right-1,5]>carlengt) then
begin integer m;
if right>100 then goto al1;
if right=0 then
begin
headrh:=if headrh=100 then 1 else headrh+1;
m:=headrh;
end
else m:=if headrh+right-1<100 then headrh+
right else headrh+right-100;
rhveh[m,1]:=time;
rhveh[m,2]:=if random(0,1.0,0)≤rhweave then
1 else 0;
rhveh[m,3]:=rhveh[m,4]:=speed(meanrh,srh);
rhveh[m,5]:=rhveh[m,6]:=0;
right:=right+1;
rightgap:=rightgap+fresh(rhvol,rhmingap);
end else rightgap:=rightgap-scan;

if leftgap<0 and (left=0 or lhveh[if headlh
+left-1>100 then headlh+left-101 else
headlh+left-1,5]>carlengt) then
begin integer m;
if left>100 then goto al2;
if left=0 then
begin
headlh:=if headlh=100 then 1 else headlh+1;
m:=headlh;
end
else m:=if headlh+left-1<100 then headlh+
left else headlh+left-100;
lhveh[m,1]:=time;
lhveh[m,2]:=if random(0,1.0,0)≤lhweave then
1 else 0;
lhveh[m,3]:=lhveh[m,4]:=speed(meanlh,slh);
lhveh[m,5]:=lhveh[m,6]:=0;

```

left:=left+1;
leftgap:=leftgap+fresh(lhvol,lhmingap)
end else leftgap:=leftgap-scan;

begin comment QUEUE CLEARANCE. Priority from
    right;
integer behind; real space, accn;
if rhq=0 or rms>0 then goto leftlane;
if rhveh[headrh,2]≠1 then goto L1;
if lhq>0 then
    begin
    go(rh,1,headrh,rhq,rhtally,lhtally,right,
        rhveh);
    goto L3
    end;

    if left=0 then
    begin
    go(rh,1,headrh,rhq,rhtally,lhtally,right,
        rhveh);
    goto L4
    end;

    behind:=look(lhveh,length,left,headlh,car
        lengt);
    if behind=2000 then goto L5;
    space:=rhveh[headrh,5]-carlengt-lhveh[behind,
        5];
    accn:=if space<0 then rhveh[headrh,4]-
        lhveh[behind,4] else alpha×((rhveh[headrh,
        4]-lhveh[behind,4])/space);
    if accn>maxdecn then go(rh,1,headrh,rhq,
        rhtally,lhtally,right,rhveh);

L5:  if rhq>0 then
    begin integer last,t;
    last:=headrh+rhq-1;
    if last>100 then last:=last-100;
    if last>headrh then
    begin
    for t:=headrh step 1 until last do if loop1
        (t,rhveh,lhveh,right,left,headrh,headlh)
        then rhq:=rhq-1;
    end
    else
    begin
    for t:=headrh step 1 until 100,1 step 1
        until last do if loop1(t,rhveh,lhveh,right,
        left,headrh,headlh) then rhq:=rhq-1;
    end;
    end;
    goto out;

```



```

L4:  if rhq>0 then
      begin integer last,t;
      last:=headrh+rhq-1;
      if last>100 then last:=last-100;
      if headrh<last then
        begin
          for t:=headrh step 1 until last do if loop2
            (t) then rhq:=rhq-1;
          end
        else
          begin
            for t:=headrh step 1 until 100,1 step 1
              until last do if loop2(t) then rhq:=rhq-1;
            end;
          end;
        goto out;

L1:  go(rh,0,headrh,rhq,rhtally,lhtally,right,
      rhveh);
      if lhq>0 then goto L3;
      if left=0 then goto L4 else goto L5;

L3:  if rhq>0 then
      begin integer last,t;
      last:=headrh+rhq-1;
      if last>100 then last:=last-100;
      if headrh<last then
        begin
          for t:=headrh step 1 until last do if loop3
            (t,rhveh,lhveh,headrh,headlh,lhq,right,
              left) then
            begin
              rhq:=rhq+1;
              lhq:=lhq-1;
            end;
          end
        else
          begin
            for t:=headrh step 1 until 100,1 step 1
              until last do if loop3(t,rhveh,lhveh,headrh,
                headlh,lhq,right,left) then
            begin
              rhq:=rhq+1;
              lhq:=lhq-1;
            end;
          end;
        end;

      if lhveh[headlh,2]=1 then
        begin
          if lms>0 then goto out;
          go(lh,1,headlh,lhq,lhtally,rhtally,left,
            lhveh);
        end;

```

```

if lhq>0 then
begin integer last,t;
last:=headlh+lhq-1;
if last>100 then last:=last-100;
if headlh<last then
begin
for t:=headlh step 1 until last do if
loop3(t,lhveh,rhveh,headlh,headrh,rhq,
left,right) then
begin
lhq:=lhq+1;
rhq:=rhq-1;
end;
end
else
begin
for t:=last step 1 until 100,1 step 1 until
last do if loop3(t,lhveh,rhveh,headlh,
headrh,rhq,left,right) then
begin
lhq:=lhq+1;
rhq:=rhq-1
end;
end;
end;
goto out;

```

```

leftlane:if lhq=0 or lms>0 then goto free;
if right=0 then goto L6;
if lhveh[headlh,2]=1 then
begin
behind:=look(rhveh,length,right,headrh,
carlengt);
if behind=2000 then goto L7;
space:=lhveh[headlh,5]-carlengt-rhveh[
behind,5];
accn:=if space<0 then lhveh[headlh,4]-rhveh
[behind,4] else alpha*((lhveh[headlh,4]-
rhveh[behind,4])/space);
if accn>maxdecn then go(lh,1,headlh,lhq,
lhtally,rhtally,left,lhveh);
end
else go(lh,0,headlh,lhq,lhtally,rhtally,
left,lhveh);

```

```

L7: if lhq>0 then
begin integer t,last;
last:=headlh+lhq-1;
if last>100 then last:=last-100;
if headlh<last then
begin
for t:=headlh step 1 until last do if loop1
(t,lhveh,rhveh,left,right,headlh,headrh)
then lhq:=lhq-1;

```



```

end
else
begin
for t:=headlh step 1 until 100,1 step 1
  until last do if loop1(t,lhveh,rhveh,left,
    right,headlh,headrh) then lhq:=lhq-1;
end;
end;
goto out;

L6:  if lhveh[headlh,2]=1 then go(lh,1,headlh,
    lhq,lhtally,rhtally,left,lhveh) else go(lh,
    0,headlh,lhq,lhtally,rhtally,left,lhveh);
    if lhq>0 then
      begin integer t,last;
        last:=headlh+lhq-1;
        if last>100 then last:=last-100;
        if last>headlh then
          begin
            for t:=headlh step 1 until last do if loop4
              (t) then lhq:=lhq-1;
          end
        else
          begin
            for t:=headlh step 1 until 100,1 step 1
              until last do if loop4(t) then lhq:=lhq-1;
          end
        end
      else goto free;

out:  if lhq>0 then
      begin integer t,v,last;
        last:=headlh+lhq-1;
        if last>100 then last:=last-100;
        v:=0;
        if last>headlh then
          begin
            for t:=headlh step 1 until last do
              begin
                lhveh[t,5]:=length-carlengt×v;
                v:=v+1
              end;
          end
        else
          begin
            for t:=headlh step 1 until 100,1 step 1 until
              last do
                begin
                  lhveh[t,5]:=length-carlengt×v;
                  v:=v+1
                end;
          end
        end
      end;
    end;
  end;
end;

```

```

if rhq>0 then
begin integer t,v,last;
last:=headrh+rhq-1;
if last>100 then last:=last-100;
v:=0;
if last>headrh then
begin
for t:=headrh step 1 until last do
begin
rhveh[t,5]:=length-carlengtXv;
v:=v+1
end;
end
else
begin
for t:=headrh step 1 until 100,1 step 1 until
last do
begin
rhveh[t,5]:=length-carlengtXv;
v:=v+1
end;
end;
end;
end of queue clearance;

comment Vehicles beyond the end of the queue;

free: begin integer r,l;
r:=if headrh+rhq ≥ 100 then headrh+rhq-100
else headrh+rhq;
l:=if headlh+lhq ≥ 100 then headlh+lhq-100
else headlh+lhq;
goto decide;

shift:if r>(if headrh+right>100 then headrh+right
-100 else headrh+right) and l>(if headlh+
left>100 then headlh+left-100 else headlh+
left) then goto acceleration;

if r>(if headrh+right>100 then headrh+right
-100 else headrh+right) then
begin
l:=if l=100 then 1 else l+1;
goto decide
end;

if l>(if headlh+left>100 then headlh+left-
100 else headlh+left) then
begin
r:=if r=100 then 1 else r+1;
goto decide
end;

l:=if l=100 then 1 else l+1;
r:=if r=100 then 1 else r+1;

```



```

decide: if rhveh[r,2]=1 or lhveh[l,2]=1 then
      begin comment Next non-weaved vehicle;
      if rhveh[r,2]=1 then scramble(rhveh, lhveh,
      headrh, headlh, right, left, r, gauche, shift);

gauche: if lhveh[l,2]=1 then scramble(lhveh, rhveh,
      headlh, headrh, left, right, l, shift, shift);
      end;
      goto shift;
      end;

acceleration: begin comment Compute acceleration
      for each vehicle;

      procedure acc(start, finish, veh);
      integer start, finish;
      real array veh;
      begin integer count, front, rear;
      real spacing, accn1, accn2;
      for count:=start step 1 until finish
      do
      begin
      front:=if count>100 then count-100
      else count;
      rear:=if count≥100 then count-99 else
      count+1;
      spacing:=veh[front,5]-carlengt-veh
      [rear,5];
      if spacing<0 then goto a15;
      accn1:=if veh[rear,2]=1 then alphax
      ((-veh[rear,4])/(length-veh[rear,5]))
      else 1000;
      accn2:=alphax((veh[front,4]-veh[rear,
      4])/spacing);
      veh[rear,6]:=if accn1<accn2 then accn1
      else accn2;
      if veh[rear,6]>maxaccn then veh[rear,
      6]:=maxaccn;
      end;
      end of acc;

      if right>0 then
      begin
      if rhq=0 then
      begin
      rhveh[headrh,6]:=if rhveh[headrh,5]>length
      then 0 else if rhveh[headrh,2]=1 then
      alphax((-rhveh[headrh,4])/(length-rhveh
      [headrh,5])) else alphax((rhveh[headrh,3]
      -rhveh[headrh,4])/(length-rhveh[headrh,5]));
      if rhveh[headrh,6]>maxaccn then rhveh[headrh,
      6]:=maxaccn;

      if right>1 then acc(headrh, headrh+right-2,

```

```

    rhveh);
end
else
begin
if rhq<right then acc(headrh+rhq-1,headrh+
right-2,rhveh);
end;
end;

if left>0 then
begin
if lhq=0 then
begin
lhveh[headlh,6]:=if lhveh[headlh,5]>length
then 0 else if lhveh[headlh,2]=1 then
alphaX((-lhveh[headlh,4])/(length-lhveh
[headlh,5])) else alphaX((lhveh[headlh,3]
-lhveh[headlh,4])/(length-lhveh[headlh,5]));
if lhveh[headlh,6]>maxaccn then lhveh[headlh,
6]:=maxaccn;

if left>1 then acc(headlh,headlh+left-2,
lhveh);
end
else
begin
if lhq<left then acc(headlh+lhq-1,headlh+
left-2,lhveh);
end;
end;
end of acceleration;

goto start;

```

comment PRINT OUT;

```

stop: if posn=1 then
begin comment PRINTOUT of vehicle positions;

write text(30,[[p]at*time*]);
write(30,layout([ndddd.ddcc]),time);

write text(30,[[14s]left*hand*lane[32s]right
*hand*lane[cc]number*of*vehicles*discharged
[c]since*start*of*run*=*]);
write(30,layout([ndddd]),lhtally);

write text(30,[[37s]]);
write(30,layout([nddddcc]),rhtally);

write text(30,[queue*length[8s]]);
write(30,layout([-ndddd]),lhq);
write text(30,[[36s]]);

```



```

write(30,layout([-nddddcc]),rhq);

write text(30,[number*arrival*turn*entry*
present*position*acceleration****number
*arrival*turn*entry*present*position*acc
eleration[c8s]time[8s]speed**speed[36s]
time[8s]speed**speed[cc]]);

begin integer z,p,ll,q,s;
p:=headlh; ll:=0; q:=headrh; s:=0;
reprint:if ll<left then
begin
write(30,f[1],p);
for z:=1 step 1 until 6 do write(30,f[z+1],
lhveh[p,z]);
write text(30,[[7s]]);
end
else write text(30,[[60s]]);

if s<right then
begin
write(30,f[1],q);
for z:=1 step 1 until 6 do write(30,f[z+1],
rhveh[q,z]);
end;

write text(30,[[c]]);

p:=if p = 100 then 1 else p+1; ll:=ll+1;
q:=if q=100 then 1 else q+1; s:=s+1;
if ll>left and s>right then goto delae else
goto reprint
end;
end;

delae:if delays=1 then
begin comment PRINT OUT of delay values;
integer m,n,o;
writetext(30,[[cc]delays*at*time*]);
write(30,layout([-ndddsddd.dds]),time);

writetext(30,[seconds[cc27s]total*delay***
number*of*vehicles[10s]average*delay*
(secs)[c29s](secs)***delayed*undelayed*
total**per*vehicle*per*delayed*vehicle]);

for n:=1,2 do
begin comment n=1 for right hand lane;
if n=1 then writetext(30,[[ccsss]right*hand
*lane[cc]]) else writetext(30,[[ccsss]left
*hand*lane[cc]]);
for m:=1,2 do
begin comment m=1 for non-weaving traffic;
delay[n,m,4]:=delay[n,m,2]+delay[n,m,3];
delay[n,m,5]:=if delay[n,m,4]=0 then 0
else delay[n,m,1]/delay[n,m,4];

```

```

delay[n,m,6]:=if delay[n,m,2]=0 then 0 else
  delay[n,m,1]/delay[n,m,2];
if m=1 then writetext(30,[non-weaving*traffic
*only*]) else writetext(30,[weaved*traffic*
arriving[c]in*this*lane[14s]);
for o:=1 step 1 until 6 do write(30,form[o],
  delay[n,m,o]);
end;
end;
end;
goto finish;

a11: write text(30,[right*hand*lane*section*
  capacity*exceeded*at*time*]);
write(30,layout([ndddd.ddp]),time);
goto nextrun;

a12: write text(30,[left*hand*lane*section*cap
  acity*exceeded*at*time*]);
write(30,layout([ndddd.ddp]),time);
goto nextrun;

a13: write text(30,[right*hand*lane*jammed*at*
  time]);
write(30,layout([ndddd.ddp]),time);
goto nextrun;

a14: write text(30,[left*hand*lane*jammed*at*
  time]);
write(30,layout([ndddd.ddp]),time);
goto nextrun;

a15: writetext(30,[collision*failure*at*time]);
write(30,layout([ndddd.ddp]),time);
goto nextrun;

finish:if k<print then goto kay;

nextrun:
end of repeat;
end of program;

reject:close(30);

end

```


3.5.5 Procedures

An Algol procedure provides a facility similar to that of a sub-routine in a machine coded program. It enables the programmer to use a single piece of program in a number of places in his program without having to re-write it on each occasion to suit new parameters. The procedures used in the weaving simulation program are listed below, and their functions explained.

3.5.5.1 Random

This procedure is designed to generate the random numbers required by the program. Its mode of operation has been described previously in Section 1.2.4.

3.5.5.2 Speed

'Speed' generates an entry speed for a newly arrived vehicle, and is used by Segment 11 (fig. 3.4 and 3.7). (cf. Section 1.3.5 and Appendix IV for a further discussion of the method.) It requires as input the mean and range of the distribution from which the sample speed is desired.

3.5.5.3 Fresh

'Fresh' generates a new gap, and it is used in Segment 11 (figs. 3.4 and 3.7). It samples from a shifted negative exponential distribution as described in Section 1.2.3, and requires as input the hourly volume and the minimum gap required.

3.5.5.4 Look

'Look' searches for the vehicle in the opposite lane immediately behind a vehicle requiring to merge. If there is a vehicle alongside the weaving vehicle, 'look' is assigned the value 2000. If there is no vehicle behind the weaving vehicle, 'look' is assigned the value 1000. The required input

parameters are detailed as a comment in the text of the program (Section 3.5.4). This procedure is called in Segments 12 and 13.

(This procedure, together with the others described above, are suitable for external compilation in the Egdon system. Those described below must, in the form shown in the program text, be compiled internally.)

3.5.5.5 Update

The flow diagram for this procedure is described in Section 3.4.3 and shown on fig. 3.6. It is called, once for each lane, by Segment 10, fig. 3.4. The input parameters are detailed as a comment in the program text (Section 3.5.4).

3.5.5.6 Laneswap

'Laneswap' removes the vehicle from the lane in which it is travelling, and inserts it in the opposite lane in front of the vehicle found by the procedure 'look'. All the information pertaining to the weaving vehicle is transferred to the appropriate array. Necessary input parameters are listed in the program text.

3.5.5.7 Go

The procedure 'go' is called whenever a vehicle is discharged from the head of queue. It subtracts one vehicle from the queue, changes the head indicator ('headrh' or 'headlh' as appropriate), adds to the delay store (see Section 3.5.6), and adds one to the count of vehicles leaving the section ('rhtally' or 'lhtally', as appropriate).

3.5.5.8 Loop 1

The flow diagram for 'loop 1' is shown in fig. 3.15, and fig. 3.17, and is called during the queue clearance routine under labels 'L5' and 'L7'. It requires as input

- i) The number of the vehicle under consideration.

- ii) The array appropriate to the lane under consideration.
- iii) The array appropriate to the opposite lane.
- iv) The number of vehicles in the lane under consideration.
- v) The number of vehicles in the opposite lane.
- vi) The number of the first vehicle in the lane under consideration.
- vii) The number of the first vehicle in the opposite lane.

The 'lane under consideration' is the right hand lane when the procedure is called under label L5, and the left hand lane when called under L7. 'Loop 1' is a boolean procedure which assumes the value 'true' if the vehicle under consideration is a weaving vehicle which is able to change lanes, or 'false' if not.

3.5.5.9 Loop 2

'Loop 2' is called under label L4 as part of the queue clearance logic (Segment 12). The flow diagram is shown on fig. 3.14. It requires as input merely the number of the vehicle under consideration, and assumes the value true if the vehicle requires to weave.

3.5.5.10 Loop 3

'Loop 3' is called under label L3 as part of the queue clearance logic (Segment 12). The flow diagram is shown on fig. 3.13. It requires as input

- i) The number of the vehicle under consideration
- ii) The appropriate array for the vehicle under consideration

- iii) The array appropriate to the opposite lane
- iv) The number of the first vehicle in the array under consideration
- v) The number of the first vehicle in the opposite lane
- vi) The number of vehicles in the queue in the opposite lane ('lhq' or 'rhq')
- vii) The number of vehicles in the lane under consideration
- viii) The number of vehicles in the opposite lane.

'Loop 3' is a boolean procedure which takes the value 'true' if the vehicle is a weaving vehicle which is able to change lanes.

3.5.5.11 Loop 4

'Loop 4' is called as part of the queue clearance logic, and is shown on fig. 3.16 under label L6. It requires as input merely the number of the vehicle under consideration, and takes the value 'true' if this vehicle is a weaving vehicle.

3.5.5.12 Scramble

The purpose of the procedure 'scramble' is explained by the flow diagram on fig. 3.19. It is called under Segment 13, and requires as input

- i) The array appropriate to the lane under consideration,
- ii) The array appropriate to the opposite lane,
- iii) The number of first vehicle in the lane under consideration.

- iv) The number of first vehicle in the opposite lane,
- v) The number of vehicles in the lane under consideration,
- vi) The number of vehicles in the opposite lane,
- vii) A label to go to when the procedure is exited for the first time,
- viii) A label to go to when the procedure is exited for the second time.

3.5.6 Delay Storage

Delays are stored in a three-dimensional real array 'delay'. The first dimension describes the lane from which the vehicle was discharged (1 for right hand lane, 2 for left); the second dimension describes whether the vehicle was a weaving vehicle (1 for non-weaving vehicles, 2 for weaving); and the third dimension holds

- i) The total delay to vehicles in the categories described by dimensions 1 and 2,
- ii) The number of delayed vehicles,
- iii) The number of undelayed vehicles,
- iv) The sum of (ii) and (iii),
- v) The average delay/vehicle,
- vi) The average delay/delayed vehicle.

Delay values are printed out at any time requested during the run. All delays are given in seconds.

3.6 PROGRAM TESTING

3.6.1 Mechanical Tests

The mechanical tests were similar in nature to those described in Section 2, i.e., they merely consisted of requests for particular traffic configurations, and an inspection of the output to check whether the requested configuration had, in fact, been produced. The requested traffic configurations are shown in fig. 3.23. For example, referring to the configuration 1 in the figure, the proportion of weaving vehicles in each lane requested was zero. The output was then examined to check that no delays for weaving vehicles had been calculated. Similar examinations were made for configurations 2 - 9 in the light of the input data. After some minor programming changes, the program was found to be functioning in the manner intended.

3.6.2 Calibration Testing

Despite the acknowledged importance of calibrating the model, no calibration tests were carried out. In order to test the model thoroughly, it would be necessary to measure all of the input parameters simultaneously. This exercise was simply beyond the resources of the project, both in terms of manpower and equipment, but principally manpower. The parameter causing the most difficulty was characteristic speed. It has been mentioned previously that this quantity is extremely difficult to measure, and is especially so on a weaving section, owing to the large and quickly changing relative lateral displacements of the vehicles using the section. The lack of any model calibration is regrettable but unavoidable. Further reference to this situation will be made in Section 3.7.3.

3.6.3 Running Times

The program was rather extravagant with computer time, at least, compared with the traffic signals program. Computation times varied with the number of vehicle hours spent in the system, but, for the data used and described

in Section 3.7, averaged about 15 mins. computer time to simulate 1h. real time, a time advantage of 4. This figure will be less for a long weaving section with high weaving volumes, and greater for short sections with low weaving volumes. (These figures apply to the Egtran compiler only.)

3.7 PRODUCTION RUNS

It was considered impossible in this work to investigate the effect of variations in every input parameter, because of the enormous amount of computer time that would be necessary. Some of the parameters were therefore held constant for all, or most of, the runs, and held constant at values which were felt to be representative of typical traffic conditions.

3.7.1 Constant Input Parameters

3.7.1.1 Car Following Data

The car following parameters, characteristic speed and driver reaction time, have already been discussed in Sections 3.2.5 and 3.2.6. It was impossible to obtain car following data for traffic on weaving sections because the large lateral displacements of following vehicles made photography impossible. It is considered that the data obtained by Constantine and Young at Sheffield represented conditions on weaving sections reasonably closely, i.e., heavy traffic in city centre conditions.

Observations were made on a two-lane dual carriageway from Wicker to Fitzallen Square in Sheffield on a typical weekday afternoon. Fourteen vehicles were observed for a total time of 480s, and the results analysed in the fashion described in ref. 3.14. 60 manoeuvres were examined, and the correlations between behaviour predicted by the reciprocal spacing car following law and actual behaviour were computed.

The author, considering these results, decided to reject those giving correlation coefficients of less than 0.7 as being unreliable, and the remaining results are shown in Table 3.1. Two measures of the reliability of these remaining results are available: the correlation coefficient, and the time over which the observations were made. Clearly, the larger either of these two quantities are, the more reliable are predictions of a and T made from them. An attempt to allow for these differing degrees of reliability was made by weighting each result by its particular coefficient of correlation and

its particular time of observation. This weighting was achieved by simply multiplying each value of a and T by each of the weighting factors. This weighting procedure is entirely arbitrary in the sense that it is not known whether observation time or correlation coefficient is the more powerful indicator of reliability: the weighting method as it stands means that time of observation is by far the more powerful because, of course, all the correlation coefficients vary between 0.7 and 1.0, whereas observation times vary between 5 and 80s. However, since any correlation coefficient over 0.7 was judged to be highly significant, this imbalance between the weighting factors is probably unimportant. It is felt that the method as described here is preferable to merely averaging the results as they stand.

The average value of characteristic speed obtained was 18.18 ft/s, and the average driver reaction time was found to be 0.7027s. It was decided to use 18 ft/s and 0.70s as input in the production runs as being representative of typical values for British conditions, in the absence of any other data. (It should be borne in mind, when assessing the value of this admittedly small amount of data, that the collection of such data is an extremely time consuming business - cf. ref. 3.14.)

3.7.1.2 Car Lengths

Vehicles on British roads vary in length from 9ft 9ins. (Fiat 500, ref. 3.24) to 49 ft 2½ ins (largest articulated vehicle allowed under 1968 Construction and Use Regulations, cf. ref. 3.25). The average length of road space occupied by a stationary vehicle was required in the model in order to calculate queue lengths, and also in the lane changing logic. The average length of road space occupied by a stationary vehicle is not, of course, the same as the vehicle's physical length.

DOCKERTY (1966, ref. 3.26) described some work at Birmingham University on queueing at signalised intersections in connection with area traffic control research. Eight arms in the Holborn area of London were observed using closed circuit television, and the equation

$$Q = 13.5 + 16.26N$$

obtained by using linear regression analysis on all the data (Q = Queue length, N = Number of queueing vehicles). The equation, as it stands, produces the surprising result that when the number of queueing vehicles is zero the length of the queue is 13.5 ft. In view of this anomaly, the value of 16.26 (the gradient) must be treated with a certain amount of caution if used as the average length of a queueing vehicle. The analysis would have been more useful had the regression line been restrained to pass through the origin.

SEDDON, (1968) in some unpublished work on the dispersion of traffic platoons, at Salford University, investigated the 'effective length' of vehicles queueing at traffic signals. The results of this work are shown in Table 3.2. The overall mean 'effective length' is obviously sensitive to proportions in the mix of traffic at any particular intersection. The site investigated by Seddon was in Salford: the junction between the A6 and Oldfield Road, and the arm observed was heavily loaded with commuter traffic in the evening peak period. These are the traffic conditions under which an urban weaving section would be expected to operate and so no further adjustments were made in the mean 'effective length'. A value of 21 ft. was used as input to the program.

3.7.1.3 Accelerations

Accelerations and decelerations attainable by road vehicles under ideal conditions vary considerably. It is theoretically possible for a vehicle to attain deceleration rates of $-g$ given perfect tyres and road surfaces, but obviously such conditions rarely obtain. Maximum accelerations will depend upon a number of factors, the most important being engine power, vehicle weight and tyre/road adhesion. However, under ordinary urban driving conditions one would not expect that these maximum performance capacities would often be utilised. In the program logic (Sections 3.4.3 and 3.4.5) the concept of 'average maximum tolerable acceleration' has been used. This quantity may be described as the maximum acceleration that a driver is prepared to impose on his vehicle, himself, and any passengers under

normal, everyday, urban traffic conditions. Clearly there will be great variation over the population of vehicle/driver combinations, but an average figure has been used for simplicity. The problem was to make a reasonable estimate of the value of this quantity, always supposing that it did in fact exist.

It was decided to investigate the accelerations and decelerations imposed upon an average family car driven in average traffic conditions, using the equipment described in Section 4.5. The car chosen was a British Leyland 'Mini', as being representative of vehicles in use at the time of the experiment. (Attempts were made to measure the acceleration potentials of a Manchester City Transport bus, but unfortunately a camera malfunction occurred on the only occasion that the vehicle was available.) The car was driven around Manchester on a weekday at 10 a.m., and the driver was requested to 'drive normally'. The reading on the accelerameter was photographed at 0.5s intervals - approx. 3000 frames were exposed whilst the vehicle was accelerating, and 3000 whilst it was decelerating. The accelerations were then read from the developed film and plotted as figs. 3.24 and 3.25. Along the x-axis of each figure is the acceleration expressed as a proportion of g , and the ordinate shows the proportion of time for which the particular acceleration was exceeded. Occasionally the driver was requested to drive the car at its maximum acceleration and deceleration, and these values may be seen on the graphs where the curve intersects the abscissa ($22\%g$ and $-23\%g$, representing 7.1 and -7.4 ft/s^2 respectively). The normal maxima as required by the program would be less than these values. It was therefore arbitrarily decided to use in the program those values which were exceeded 10% of the time, corresponding to accelerations of 4.5 and -5.0 ft/s^2 .

The author is aware of the many sources of error in these values, as discussed in the remarks beginning this section. However, in the absence of any other data, it is felt that they are not too unreasonable. If further data should come to light in the future, it would be a simple matter to change these acceleration values - they are entered as items of input data on the data tape.

3.7.1.4 Speeds and Speed Distributions

The generation of speed distributions is discussed in Appendix VIII. In order to investigate speed distributions at an actual site, observations were made at a weaving section entrance in Birmingham. Fig. 3.26 shows the site layout and camera position. The site was chosen because, at the time (1966), it was the only long weaving section in an urban area known to the author. The section under study was the south side of the Circus, and was about 450 ft. long and 40 ft. wide.

Speeds were measured by setting out a grid of known dimensions on the road and by photographing the vehicles with the time lapse equipment as they moved over the grid. (This photographic technique was used in preference to the more usual methods of measuring speeds such as radar and electronic timing because it allowed the arrival gap distribution to be observed simultaneously - see Section 3.7.1.5). The relative displacement of vehicles on the grid between successive frames enabled the vehicle speeds to be quickly and easily abstracted. The results are presented as the histograms in Fig. 3.27, and further details are given in Table 3.3.

Examination of the speed distributions shows that, even on a well designed weaving section such as St. Martins Circus, an unofficial 'priority rule' exists: the traffic approaching along Bull Ring slows to a crawl whilst awaiting gaps in the traffic already on the Circus. This effect is exaggerated to a certain extent by the upgrade on the Bull Ring and the downgrade on the Circus, but the speed distributions nevertheless indicate that some driver education is necessary in such situations. Some more adventurous drivers did venture onto the section whilst traffic was already on the Circus, but they were few and far between. The Bull Ring speed distribution is further distorted by the presence of traffic signals approximately 200 yds. away, but the St. Martins Circus traffic was uninterrupted. This probably accounts for the larger coefficient of variation (standard deviation/mean) for the Bull Ring distribution (see Table 3.3). The coefficient of variation for the St. Martins Circus traffic was considered close enough to that specified in Appendix VIII (0.19) to warrant adoption of the speed generation procedure

described in that Appendix.

The mean speed will, of course, be dependent upon the volume. Various attempts have been made to express this relationship in a precise form, but experimental verification of these theories is scarce. Because of the lack of experimental data and for ease of comparison of the results of the simulation studies, the effect of volume on entry speed has therefore been ignored at this stage. It would be easy to allow for it, however, merely by changing the mean entry speeds on the data tape for each input volume.

The entry speed of each vehicle entering the section has been used to define the 'desired' speed of the vehicle. The vehicle's 'desired' speed on the weaving section, however, is likely to be lower than the speed 'desired' on the open road. This means that a single vehicle on an empty section would enter at a lower speed, because of the usual geometric restrictions at the entry point, and leave at a speed close to its 'desired' open road speed. Again, this effect, if it exists, has been ignored, in order that any delays calculated may be attributed to other traffic on the section, and not to geometric design considerations.

Despite the observation of the low mean speeds in Birmingham, it was intuitively felt that 20 mile/h would be a reasonable mean desired speed for vehicles using future urban weaving sections. Under crowded conditions the vehicles entering the section will, in any case, be forced to slow down by other traffic on the section, weaving or not. Again, the arbitrary nature of this assumption is not denied, but it was felt that the Birmingham mean speeds observed were depressed by purely local conditions, i.e., the upgrade and signals on Bull Ring, and left turning traffic and tight horizontal curves on St. Martins Circus. Since all speeds in the program are handled as ft/s. input means for both lanes were 30ft/s (20 mile/h. approx.). The input 'range' was 15ft/s. (It should be stressed that these parameters are easily changed since they are input to the program - not built into the program.)

3.7.1.5 Arrival Gap Distributions

The arrival gap distributions for Bull Ring and St. Martins Circus were obtained from the films used for the speed distributions. A camera speed of 4 frames/s was used, and so the arrival gaps have been measured to the nearest 0.25s. The distributions are shown in fig. 3.28, and further details of the observations are given in Table 3.3. The arrival distribution used in the program is the shifted exponential distribution. Inspection of the histograms in fig. 3.28 shows that the correspondence between a shifted exponential distribution and the observed distribution is not good, principally because of the presence of very small gaps in the observed distribution. The small gaps are present because the weaving section entrance observed was a two-lane entrance. Use of the shifted exponential distribution is convenient, however, for the same reasons as in the traffic signal simulation - namely, that the program can only cope with one arrival at each entrance at any one scanning time (see Section 2.2.3 for a fuller discussion of this point). Therefore the same restriction in the use of the distribution applies when used in the weaving program as that which applies in the traffic signals program, i.e. that the minimum arrival headway must be equal to, or greater than, the scanning interval. Since the scanning interval must be the same as the driver reaction time, a minimum headway of 0.7s was used. Volumes were varied as described in Section 3.7.3.

3.7.2. Simulation Times

For purely administrative reasons, it was decided that 20 minutes was the most computer time that could reasonably be asked of the Computer Department of the University of Salford at any one time. This therefore effectively fixed the maximum simulation time that could be obtained from any one run at 1 hour. The difference in the results produced by the program with a simulation time of one hour, and longer simulation times is therefore unknown. This is regrettable, but in the circumstances obtaining at the time of the work, unavoidable. It was possible, however, to obtain printouts of the results at simulation times of less than one hour, and for some of the runs printouts were obtained at times of 2200, 2400, 2600, 2800, 3000, 3200, 3400 and 3600s. The values of average delay per vehicle were observed

to vary $\pm 5\%$ from the average delay per vehicle given for a simulation time of 3600s. It is likely, therefore, that longer simulation times would not produce substantially different results.

3.7.3 Variable Input Data and Results

3.7.3.1 Starting Random Numbers

The starting random numbers were chosen in a manner similar to that described in Section 2.5.3. They are shown in Table 3.4.

3.7.3.2 Effect of Section Length on Delays

Intuitively, one would expect the capacity of a weaving section to be directly proportional to its length, and inspection of fig. 7.4 in ref. 2.13 bears out this expectation. This chart also indicates that the capacity of a weaving section 1000 ft. long should be between 1500 and 3750 veh/h. It is difficult to be more precise than this, because the manual makes use of such factors as 'quality of flow' and 'weaving influence factor' to determine capacity, and it is impossible to know which values of these two quantities apply to the traffic being simulated in this work. Also the manual is not directly comparable to this work because it assumes that all non-weaving traffic is accommodated in extra lanes parallel to the two or more weaving lanes: this is not the case in the model being simulated, and hence one may expect the capacity of the simulated system to be somewhat lower than that predicted by the manual. At this stage, however, the ultimate capacity of the model is not important, but the fact that the manual predicts increase in capacity with increase in length is important. It follows from this that it would be reasonable to expect a decrease in delay with an increase in length, all traffic volumes being constant, because the degree of saturation of the section would decrease. It was decided to use the model to test this hypothesis.

Five lengths were simulated, with approach volumes of 600 veh/h in each lane, the proportion of weaving traffic being 30% in each lane (a total weaving volume of 360 veh/h). The results are shown in Table 3.5 and

as the dotted line in fig. 3.29. The results exhibit two surprising characteristics: the delays increase with an increase in length; the delays also appear to be far too high, in view of the fact that ref. 2.13 indicates that, with 360 weaving vehicles per hour, it is not operating at anywhere near capacity. Inspection of the output showed that most vehicles were moving through the section at the crawling speed of 5ft/s (see Section 3.4.3), and that this speed was attained soon after the vehicles had entered the section. Fig. 3.30 shows this effect more clearly. The dotted curves trace the speed of a single weaving vehicle, unable to weave, as it moves through a section 600, 1000 and 1400 ft. long. It may be seen that the vehicle reaches the crawling speed of 5ft/s well before it reaches the end of the section. Any vehicle following closely behind will be forced to slow down slightly earlier, and in this way, a queue of slow moving vehicles builds back towards the section entrance. Since the queues in both lanes are moving at the same speed, no change in the relative positions of the vehicles in each lane occurs. Hence, if no weaving opportunity has been presented to a weaving vehicle before the crawling speed is reached, no such opportunity will become available until the end of the section is reached. (It might be possible to correct this by allotting a slightly different crawling speed to each lane. Unfortunately, the crawling speed of 5ft/s was not made an item to be read in on the data tape, but was built into the program. A small programming change would therefore be necessary. It would be a reasonable change to make, in a traffic behaviour sense, where a priority rule is in operation.) This, then, accounts for the high delays exhibited in fig. 3.29.

It is unlikely that drivers do, in fact, behave in the manner shown by the dotted line in fig. 3.30, although the author has no data to prove this contention. It is more likely that drivers adjust their speed so as to decelerate over the whole length of the section and draw to a halt at the end of the section. It is possible to reproduce this effect by decreasing the value of the characteristic speed used in the car following formula

(see Section 3.2.3). The solid lines in fig. 3.30 trace the progress of a vehicle through the section, when using a value of 10ft/s for the characteristic speed. It may be seen that the crawling speed is reached at a point much closer to the section exit. (Table 3.7 shows the delays incurred by vehicles whose progress is traced in fig. 3.30.) The difficulty about using a characteristic speed as low as 10ft/s or even lower, is that no-one has ever observed a value as low as this, although none of the observations to date have been made on weaving sections. It can be justified, however, if Greenbergs Fundamental Diagram of Traffic (ref. 3.11) is accepted, which states that:-

$$V = V_m \ln (k_j / k)$$

where V = Speed

V_m = Mean speed when flow is a maximum

k = Concentration

k_j = Concentration in jam conditions.

It can be shown (ref. 3.9 or 3.12) that V_m corresponds to the constant 'characteristic speed' used in the reciprocal spacing car following law, i.e. characteristic speed may be interpreted as the speed at which maximum flow occurs. Now, in their work on the capacity of weaving sections, the Road Research Laboratory (ref. 3.5) observed that maximum flow occurred at a speed of 10 mile/h (14ft/s), and this may well be an indication of the value of the characteristic speed on weaving sections.

The fact that the delay is extremely sensitive to the characteristic speed is shown in Table 3.8 and fig. 3.31. The value of characteristic speed was changed whilst all other variables were held constant: traffic volumes were 600 veh/h in each lane, and the proportion of weaving vehicles was 30% in each lane. It may be seen that changing the value of the characteristic speed from 12ft/s to 18ft/s causes the model to change its behaviour from that of a lightly loaded system to a heavily loaded system.

Does the car following theory apply to the weaving traffic?

The effect of changing the value of the characteristic speed from 18ft/s to 10ft/s is also shown by the solid line in fig. 3.29, and in Table 3.6. Here it may be seen that the values of the delays have been drastically reduced, but it may also be seen that the delay still increases with an increase in the length of the section. The reason for this is not known: the most reasonable explanation that occurs to the author is that car following theory - or, at least, the reciprocal spacing law - cannot be adapted for uses of this kind, and that it only applies under the conditions under which it was examined, i.e. two vehicles travelling close together at fairly constant speeds. Another possibility is that the car following theory does apply, but that the value of the characteristic speed is different for different lengths of section. If this were true, however, the characteristic speed would have to be high at short lengths and low at long lengths for the delay curve to decrease with an increase in length. Bearing in mind the remarks made about the connection between characteristic speed and the speed at maximum flow, this would mean that the average speed through a short section would have to be higher than that through a long section. This, to the author, seems unlikely.

It should perhaps be pointed out at this stage that, despite the limitations of present car following theory, it is the only tool the traffic simulator has. The motion of vehicles through any system must be described somehow before any microscopic simulation can be achieved. Much more work must be done on this topic before traffic simulation can progress usefully to a greater complexity and to finer detail than the work described here.

3.7.3.3 Variation of Delay with Weaving Volume

Table 3.9 and fig. 3.32 show the effect of an increasing volume of traffic on the system. (These results were obtained using a characteristic speed of 18ft/s). The proportion of weaving vehicles was held constant at 30%, and so the increase in delay was due to both an increase in the number of weaving vehicles, and also an increase in the number of non-weaving vehicles. The length of section was constant at 1000ft. The decrease in the delay at

800 veh/h is merely due to the fact that the system was very heavily loaded at volumes of 600 veh/h and over, and therefore very unstable. (It was impossible to study the stability of the system in general because of a shortage of computer time.)

The effect of weaving volumes was studied further, and the results are shown in Table 3.10 and fig. 3.33. The characteristic speed used to obtain these results was 10ft/s. The regression line through the data has the equation:-

$$d = \exp (1.49 + 0.00204w)$$

where d is the delay/veh (s),

and w is the weaving volume (veh/h).

The correlation coefficient is 0.594, which is significant at the 0.1% level. The figure also gives some idea of the scatter in the results, if it be assumed that the total weaving volume is the only dependent variable, and that the distribution of the weaving volumes has no effect. Since the model is symmetrical, apart from the queue discharge process, it is unlikely that the distribution of weaving volumes does have a significant effect.

The apparent delay when the weaving volume is zero (4.44s) is caused by the fact that vehicles using the section are delayed by slower vehicles in front of them. Strictly speaking, therefore, this value should be subtracted to find the delay directly attributable to the effect of weaving volume.

Direct comparison between this curve and the curve obtained by the Road Research Laboratory (fig. 3.2) is impossible because the capacity of the section is not known. The shape is similar (the ordinate has been transformed to a logarithmic scale in fig. 3.33), and, coincidentally, so are the delay values. The size of the weaving section investigated by the Road Research Laboratory is not known.

In view of the remarks made about the importance of the characteristic speed (Section 3.7.3.2), the usefulness of the curve in fig. 3.33 is limited. However, the model is very flexible, in that most of the quantities are

easily changed on the data tape. The model makes a start in the understanding of the operation of weaving sections, despite the apparent limitations of the car following theory, and should prove a useful analysis tool when, and if, more and better information becomes available about car following behaviour.

CHAPTER 3 : REFERENCES

- 3.1 Vocabulary of Traffic Engineering Terms, Printerhall Ltd., London, 8.
- 3.2 NORDQVIST, S., The Concept of Practical Capacity, Proc. 6th Int. Study Wk., Salzburg, 1962.
- 3.3 WEBSTER, F.V., & J.G. WARDROP, Capacity of Urban Intersections, Proc. 6th Int. Study Wk., Salzburg, 1962.
- 3.4 WARDROP, J.G., The traffic Capacity of Weaving Sections of Roundabouts, Proc. Opns. Res. Int. Conf., 1957.
- 3.5 Research on Road Traffic, HMSO, London, 1965, 319-322.
- 3.6 Highway Capacity Manual 1965, Highw. Res. Bd. Special Rep. 87, Wash., 1965.
- 3.7 CHANDLER, R.E., R. HERMAN & E.W. MONTROLL, Traffic Dynamics: Studies in Car Following, Opns. Res., 6, 1958, 165.
- 3.8 HERMAN, R., E.W. MONTROLL, R.B. POTTS & R.W. ROTHERY, Traffic Dynamics: Analysis of Stability in Car Following, Opns. Res., 7, 1959, 86-106.
- 3.9 HERMAN, R., & R.B. POTTS, Single Lane Traffic Theory & Experiment, in HERMAN, R., (Ed.), Theory of Traffic Flow, Elsevier, 1961, 120-146.
- 3.10 GAZIS, D.C., R. HERMAN & R.B. POTTS Car-Following Theory of Steady State Traffic Flow, Opns. Res 7, 1959, 499-505.
- 3.11 GREENBERG, H., An Analysis of Traffic Flow, Opns. Res., 7, 1959, 79-85.

- 3.12 PIPES, L.A., Car Following Models & the Fundamental Diagram of Road Traffic, *Transpn. Res.*, 1 (1), May 1967, 21-29.
- 3.13 LEE, J., & J.H. JONES, Traffic Dynamics: Visual Angle Car Following Models, *Traff. Engng. & Control*, 9 (7), Nov. 1967, 348-350.
- 3.14 CONSTANTINE, T., & A.P. YOUNG, Traffic Dynamics: Car Following Studies, *Traff. Engng. & Control*, 8 (9), Jan 1967, 551-554.
- 3.15 HIGHWAY RESEARCH BOARD, Highway Capacity Manual, US Govt. Printing Office, Wash., 1950.
- 3.16 GEORGE, H.P., Methods of Measuring Traffic Volumes, Speed Delays, Traffic Capacities, presented at Summer School of Traff. Engng., Univ. Melbourne, 1955.
- 3.17 EDIE, L.C., & R.S. FOOTE, Traffic Flow in Tunnels, *Proc. Highw. Res. Bd.*, 37, 1958, 334-344.
- 3.18 MICHAELS, R.M. & L.W. COZAN, Perceptual & Field Factors causing Lateral Displacement, 42nd Ann. Meeting Highw. Res. Bd., Wash., 1963.
- 3.19 WYNN, F.H., Weaving Practices on One-Way Highways, Studies of Weaving & Merging Traffic, Bureau of Highw. Traff., Yale, 1948, 9-57.
- 3.20 KNOX, D.W., Merging & Weaving Operations in Traffic, *Proc. Australian Road Res. Bd.*, 2 (1), 1964, 10-20.
- 3.21 American Association of State Highway Officials, A Policy on Arterial Highways in Urban Areas, 1957, repr. with definitions 1962.

- 3.22 HAIGHT, F.A., E.F. BISBEE & C. WOJCIK, Some Mathematical Aspects of the Problem of Merging, Highw. Res. Bull. 356, 1962, 1-14.
- 3.23 Egdon System Reference Manual, 1, English Electric Computers, 1969, Stoke on Trent.
- 3.24 Daily Express Review of the 1966 Motor Show, Beaverbrook Newspapers, London, 1966.
- 3.25 FURNESS, J.W., Implications of Construction & Use Regulations for Road Vehicles on Transport Costs & Amenities, Instn. Civ. Engrs. Transpn. Engng. Group, 31 March, 1969.
- 3.26 DOCKERTY, A., Queue Lengths at Signalised Intersections, The Surveyor & Munic. Engr. 130, 14 Oct 1967, 26-28.

CHAPTER FOUR: EQUIPMENT

4.1 CAMERAS

Two cameras were used in data collection, either singly or in pairs. The two cameras were similar in almost every respect, apart from minor differences in some physical dimensions. The cameras are described in some detail in refs. 4.1 and 4.2, but a short description follows:-

The cameras are electrically driven at 8, 16 or 24 frames/s, or in a 'single-shot' mode. The detachable magazines contain up to 200ft of 16mm film (about 7000 frames), and the cameras will take any 'C' mount lenses. Other facilities include an electrically actuated 'event-marker' which caused an image to be photographed in the corner of the frame, and an adjustable shutter adjustable between 30 and 110°. The lenses used in this work were primarily 10mm wide angle lenses, but lenses of various focal lengths were available and used occasionally; two 25mm, one 50mm, one 75mm and one 100mm. Ordinary photographic tripods were available for mounting the cameras.

Power was supplied to the cameras from a power pack of two 6v. lead acid motorcycle accumulators in series, and the camera speeds of 8, 16 and 24 frames/s were operated via a gearbox when the electricity supply was continuous. Pulses of current were required to operate the cameras when in the 'single shot' mode. The continuous camera speeds were tested by using a stroboscope, and they were found to be inaccurate, varying according to the film load and the current supply (see ref. 4.2). Accordingly the continuous speeds were not used when a constant frame exposure rate was required, and equipment was designed to be used when the cameras were in the 'single-shot' mode. (One of the cameras, together with the 200ft. magazine and 25mm lens is shown in fig. 4.1.) A 'zoom' viewfinder with parallax adjustment was used in most of the work. When exact framing was required, a reflex viewfinder was used (which necessitated removal of the magazine).

4.2 INTERVALOMETERS

At the start of this work, no battery powered intervalometer was available commercially which gave the required frame exposure rate, and so suitable apparatus was designed (see ref. 4.1) by Constantine (1964). The functions required of an intervalometer, or time pulse unit, were the supply of a pulse of electricity at a particular voltage for a particular duration at particular time interval, and the ability to supply the above requirements in field conditions for a length of time sufficient to expose 200ft of film. The first intervalometer designed was based upon an electromechanical system of a constant speed motor driving a turntable. Attached to the turntable was a perspex cam which closed a switch allowing a pulse of current to reach the camera, thereby operating the shutter. Power was supplied by two rechargeable DEAC mercury batteries, and the unit also included a frame counter, and a volt meter to indicate the state of charge of the accumulators. Fig. 4.2 shows the unit. Although remarkable accuracy was obtained from this unit, in laboratory conditions, it proved to be rather unreliable in the field. (The performance of the device in one particular data collection exercise is discussed in Section 2.2.2.1). It also became necessary to supply two cameras with pulses at faster rates than 1 frame/s, in connection with car following data collection exercises. Attempts were made to develop the electro-mechanical device to a state where these further requirements could be satisfied but, for a variety of reasons, the chief being the inherent unreliability of mechanical systems, it was decided that a completely new device was required incorporating an electronic timing system. After considerable development effort, such a device was constructed which proved completely successful, giving remarkably accurate performances combined with excellent reliability. The device is described in detail in ref. 4.2, and is shown in fig. 4.3. The increased power requirements of the two cameras operating at higher speeds were met by using lead-acid accumulators: DEAC cells were used to drive the intervalometer timing and relay circuits.

4.3 CAR FOLLOWING EQUIPMENT

Two cameras and the electronic intervalometer were used to gather data on

car following behaviour which is referred to in Section 3.2.5. (The work is described in detail in ref. 3.14.) A test vehicle was fitted with a small frame, and attached to the frame was a forward viewing camera and a rearward viewing camera. At first a distance measuring meter driven via the speedometer cable was included in the field of view of the forward facing camera, but insufficient accuracy was obtained. Accuracy was improved with the development of a device by CONSTANTINE and YOUNG at Sheffield University (unpublished). A hub cap from the test vehicle was taken and the centre section drilled away and replaced by a brass disc about 70mm in diameter. Around the periphery of the disc were drilled 20 holes. In the centre of the disc was a simple bearing, and rigidly attached to the bearing was a 12v light bulb on the outside of the disc and a photo-sensitive transistor on the inside (see fig. 4.4). The bearing, light source and photo-transistor were restrained by a spring attached to the vehicle body work, and as the hub cap revolved pulses of light from the light source were transmitted via the holes to be registered by the photo-transistor. Thus distances could be measured to the nearest $1/20$ of the circumference of the vehicle's wheel, i.e. to the nearest 80mm approximately. Electrical pulses from the photo-transistor were shaped by a pulse-shaping circuit into a rectangular form, and were counted on an Advance SCI Counter Timer, using Decatron counters (fig. 4.5 shows the arrangement). The counter required a mains supply or equivalent to operate, and so was powered by a 12v lead acid accumulator and a transverter which converted the 12v DC current into 250v AC @ 50 Hz. By placing the counter timer in the field of view of the rear camera, the distance travelled at any time was recorded. Camera speeds of 4 frames/s were used, and the results analysed using the equipment described in the next section. The results were then further analysed on KDF9 using programs developed by Young.

4.4. PROJECTORS AND SCREENS

The requirement of a projector to be used in time lapse photography is the ability to project one frame for any length of time. Because of the heat

generated by the projector lamp, therefore, special cooling facilities are necessary. Three projectors were used in the course of this work:-

- i) Specto Analysis Projector Mk. 1
- ii) Specto Analysis Projector Mk. 11
- iii) LW Analyst Projector.

The Specto Mk. 1 was similar to an ordinary 16mm cine projector, apart from the inclusion of a switch to enable frames to be projected at 16 or 2 frames/s, or in 'single shot' mode. The Mark 11 was an improved version of the Mark 1, the main improvements being a quartz iodine lamp and power reverse. The power reverse was a great improvement over the hand reversing arrangement on the Mark 1.

The LW Analyst was a much more complex and expensive machine. Projection speeds available were 24, 16, 12, 8, 4, 2 and 1 frames/s, and 'single shot'. Film could be run through the gate in either direction at any speed. It was altogether an excellent machine which made analysis a much easier and faster process.

Films were analysed on a smaller desk-top daylight viewing screen or on a much larger screen designed by YOUNG and described in ref. 4.2.

4.5 ACCELEROMETER

Instruments providing a continuous record of vehicle accelerations are complex, and therefore expensive, items. It was therefore decided to improvise some equipment which would be simple to operate and cheap to purchase. The Tapley Brake Testing Meter is a device available commercially, which is used for testing the efficiency of a vehicle's braking system. It consists of a pendulum suspended in oil attached to a moving scale. When the vehicle under test decelerates the pendulum is displaced, thereby displacing the scale which is graduated from 0-100%. The 100% reading is obtained under ideal conditions, i.e. when a deceleration of g is experienced. The scale is fitted with a locking device which locks the scale at its maximum reading, but it is possible to use the meter without the locking device engaged.

The meter will then give a continuous indication of decelerations experienced by the vehicle. The meter is mounted in a bracket which may be adjusted so that the instrument is level and a reading of 0% is shown on the scale. Unfortunately the meter will read accelerations in one direction only - it is impossible to measure accelerations and decelerations with the instrument in the same configuration. A locking screw in the bracket allows the instrument to be rotated through 180° quickly and easily however.

The meter and bracket were mounted on a large baseboard made of plywood (fig. 4.6 shows the arrangement). Also attached to the baseboard was a pair of vertical rods. Sliding between the rods was a clamp, and attached to the clamp was an aircraft mounting manufactured by Vinten, which is designed to facilitate the use of their cameras in aircraft. The camera was thereby mounted above the meter with the scale of the meter in the field of view. The 75mm lens was found to be suitable, giving an almost full frame photograph of the window under which the scale moved. Operation of the camera at 2 frame/s therefore sampled the deceleration or acceleration of the vehicle at 0.5s intervals and gave a permanent record on film. It was then an easy matter to run the film through the projector at a convenient speed and note the readings. A lamp was mounted above the instrument, but it was found to be unnecessary under usual daylight conditions, provided a fast film was used. (It was necessary to use a fast shutter speed in order to 'stop' movement on the scale of the meter.)

Accuracy of the meter is not known, since no attempt was made to calibrate it. The manufacturers of the meter claim an accuracy of 2%, and each meter is tested before it leaves the works by a standard NPL test. As the meter used in this work was brand new, it may be assumed that it conformed to this standard.

4.6 EVENT RECORDER

A Rustrak Model 92 4-channel event recorder was used to measure headways (cf. Section 2.2.3). The device is distributed in the U.K. by Gulton Industries (Britain) Ltd., but is of American origin. It provides for the recording of four individual channels of on-off data. Pressure sensitive paper is drawn under the heads of four styli which are displaced to one side when a signal is received along one of the channels and the signal is recorded as a rectangular trace on the paper. The paper speed on this particular instrument was 2150mm/min. Power was supplied by DEAC rechargeable cells, and the event signals by a bank of four push buttons. Since the speeds given by the manufacturer were nominal only, it was necessary to calibrate the instrument by using one of the channels to record known time intervals.

CHAPTER 4 : REFERENCES

- 4.1 CONSTANTINE, T., Time Lapse Kenematography for Traffic Studies, Traff. Engng. & Control, 5 (11), Mar 64, 661-3.
- 4.2 CONSTANTINE, T., A.P. YOUNG & M.H.E. LARCOMBE, Time Lapse Kinematography for Traffic Research, The Photographic J., Oct 66, 311-318.

Appendix I : Probit Analysis

For the purposes of this appendix, the subjects will be taken to be drivers, the stimuli gaps of various sizes, and the responses acceptance or rejection.

In general, apart from sampling errors, one would expect a plot of proportion of drivers accepting a gap of a certain size or less to increase with gap size. The problem is to find the population curve relating proportion accepting to gap size, and it is assumed that this true curve is the cumulative normal distribution:

$$p = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x_0} \exp\left[-(x-\mu)^2/2\sigma^2\right].dx \quad 1.1$$

where p = Proportion of the population accepting a gap of size x_0 or less.

μ = Mean of the normal distribution (the mean minimum acceptance gap).

σ = Standard deviation of the distribution of minimum acceptance gaps.

(x may be the gap size or the logarithm of the gap size, depending upon which gives a curve nearest to the cumulative normal distribution.)

By transforming the normal sigmoid curve by the probit transformation, a straight line is obtained. The probit Y corresponding to a proportion p is defined such that, (ref. 2.27),

$$p = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Y-5} \exp(-x^2/2).dx \quad 1.2$$

i.e., 'the abscissa which corresponds to a probability p in a normal distribution with a mean of 5 and variance 1' (ref. 2.26). (The use of the 5 is purely arbitrary and is merely to ensure that Y is always positive, thus

making tabulation easier. The relationship between probits and proportions is shown in figure 1.1.) From equations 1.1 and 1.2 it may be seen that

$$Y = 5 + \frac{1}{\sigma} (x - \mu) \quad 1.3$$

Therefore, by plotting the probits of the proportions of drivers accepting against gap size, the points may be seen to lie approximately on a straight line, and a straight line may be fitted by eye as a first approximation. If the resulting line is of the form

$$Y = a + bx \quad 1.4$$

from equations 1.3 and 1.4 that b estimates $1/\sigma$, and a estimates $(5\sigma - \mu)/\sigma$. It may be, however, that a fit by eye is considered to be insufficiently accurate, and that a more precise fit is required.

Unfortunately, it is impossible to use a conventional linear regression technique since this method requires that the variance of y be constant for all x . Since the probability of acceptance for any particular gap size is binomial in nature, (i.e. that if n drivers are exposed to a gap which, on average, a proportion p of the population will accept, the probabilities of $n, (n - 1), \dots, 2, 1$ drivers accepting are the successive terms in the expansion of $(p + Q)^n$, where $Q = 1 - p$, provided that the drivers react independently), the variance of the observed proportion accepting (p) about its mean value of p is pQ/n . That is, the variance for any particular gap size is inversely proportional to the sample size n , and proportional to p . n will vary throughout the range of gap sizes, and the value of p is unknown - only the observed proportion p is known.

These problems may be overcome by using the Principle of Maximum Likelihood, which states (ref. 2.27),

'On the basis of a random sample drawn from a population, the estimates of the parameters of the distribution function of the population are those values of the parameters which make the probability

of the observed sample a maximum.'

Suppose that a series of k gap sizes is tested in an experiment (ref. 2.26).

The probability of r responses for a particular value of k is

$$p(r) = \frac{n!}{r! (n-r)!} p^r Q^{n-r} \quad 1.4$$

The probability of a particular set of r responses for k gap sizes is

$$p(r_1) \cdot p(r_2) \cdot \dots \cdot p(r_k)$$

which is proportionate to e^L - the 'likelihood' of a set of observations - where

$$L = \sum_{r=1}^k r \cdot \log p + \sum_{r=1}^k (n-r) \cdot \log Q \quad 1.5$$

Suppose that the true curve linking the probit Y with gap size x is

$$Y = \alpha + B_x \quad 1.6$$

Now p and Q in equation 1.5 are functions of α and B in equation 1.6, and α and B must be estimated. For maximum likelihood, L must be a maximum. From equation 1.5,

$$\frac{\partial L}{\partial \alpha} = \sum \frac{r}{p} \cdot \frac{\partial p}{\partial \alpha} + \sum \frac{n-r}{Q} \cdot \frac{\partial Q}{\partial \alpha} = 0 \quad 1.7$$

$$\frac{\partial L}{\partial B} = \sum \frac{r}{p} \cdot \frac{\partial p}{\partial B} + \sum \frac{n-r}{Q} \cdot \frac{\partial Q}{\partial B} = 0 \quad 1.8$$

Equations 1.7 and 1.8 must be satisfied simultaneously for maximum likelihood, and a direct solution is impossible. An iterative technique has been developed, however (ref. 2.27).

Suppose that $L(x)$ is a function of two parameters α and β , and it is required to estimate α and β so that $\partial L / \partial \alpha$ and $\partial L / \partial \beta$ vanish. Let a and b be approximations, or guesses to, α and β . By the Taylor-Maclaurin expansion to the first order of small quantities,

$$\frac{\partial L}{\partial a} + \delta \alpha \cdot \frac{\partial^2 L}{\partial a^2} + \delta \beta \cdot \frac{\partial^2 L}{\partial a \partial b} = 0$$

$$\frac{\partial L}{\partial b} + \delta \alpha \cdot \frac{\partial^2 L}{\partial a \partial b} + \delta \beta \cdot \frac{\partial^2 L}{\partial b^2} = 0 \quad 1.9$$

(α becomes equal to a , and β to b after differentiation.) From equation 1.5.

$$\begin{aligned} \frac{\partial L}{\partial a} &= \sum \frac{r}{p} \cdot \frac{\partial p}{\partial a} + \sum \frac{(n-r)}{q} \cdot \frac{\partial q}{\partial a} \\ &= \sum \frac{n}{pq} (p-p) \cdot \frac{\partial p}{\partial a} \quad \text{where } np = r \quad 1.10 \end{aligned}$$

Similarly,

$$\frac{\partial L}{\partial \beta} = \sum \frac{n(p-p)}{pq} \cdot \frac{\partial p}{\partial \beta} \quad 1.11$$

By substituting for $\partial L / \partial a$, $\partial^2 L / \partial a^2$ etc. from equations 1.10 and 1.11 and putting $p = p$, equations 1.9 become

$$\delta a \sum \frac{n}{pq} \left(\frac{\partial p}{\partial a} \right)^2 + \delta b \sum \frac{n}{pq} \cdot \frac{\partial p}{\partial a} \cdot \frac{\partial p}{\partial a} = \sum \frac{n(p-p)}{pq} \cdot \frac{\partial p}{\partial a}$$

$$\delta a \sum \frac{n}{pq} \cdot \frac{\partial p}{\partial a} \cdot \frac{\partial p}{\partial b} + \delta b \sum \frac{n}{pq} \left(\frac{\partial p}{\partial b} \right)^2 = \sum \frac{n(p-p)}{pq} \cdot \frac{\partial p}{\partial b} \quad 1.12$$

It is assumed that (equation 1.1)

$$p = \frac{1}{\sigma \sqrt{2\pi}} \int_{-\infty}^x \exp \left[- (x - \mu)^2 / 2\sigma^2 \right] \cdot dx$$

and that (equation 1.6)

$$Y = \alpha + \beta x$$

where (equation 1.2)

$$P = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Y-5} \exp(-x^2/2) \cdot dx$$

But,

$$\frac{\partial P}{\partial Y} = \frac{1}{\sqrt{2\pi}} \cdot \exp[-(Y-5)^2/2] \equiv Z(\text{say}) \quad 1.13$$

and

$$\frac{\partial P}{\partial \alpha} = \frac{\partial P}{\partial Y} \cdot \frac{\partial Y}{\partial \alpha} = Z$$

and

$$\frac{\partial P}{\partial \beta} = \frac{\partial P}{\partial Y} \cdot \frac{\partial Y}{\partial \beta} = Zx$$

Thus, if a and b are first approximations to α and β , better approximations are given by $a + \delta a$, $b + \delta b$, where

$$\begin{aligned} \delta a \sum \frac{nZ^2}{PQ} + \delta b \sum \frac{nZ^2}{PQ} \cdot x &= \sum \frac{nZ^2}{PQ} \left(\frac{P-P}{Z} \right) \\ \delta a \sum \frac{nZ^2}{PQ} \cdot x + \delta b \sum \frac{nZ^2}{PQ} \cdot x^2 &= \sum \frac{nZ^2}{PQ} \left(\frac{P-P}{Z} \right) x \end{aligned} \quad 1.16$$

Equations 1.16 are those that would be obtained for the linear regression of $(p - P)/Z$ on x , the weight for each point being taken as nZ^2/PQ . The line obtained is

$$(p - P)/Z = \delta a + \delta b \cdot x \quad 1.17$$

which, when combined with the first approximation

$$Y = a + bx \quad 1.4$$

gives

$$Y + \frac{p - P}{Z} = (a + \delta a) + (b + \delta b) x \quad 1.18$$

Therefore by fitting, by least squares, a line through the points x , $Y + (p - P)/Z$,

each point having weight nZ^2/pQ , and writing y for $Y + (p - P)/Z$, the line

$$y = a^1 + b^1 x \quad 1.19$$

is obtained, giving a better fit than

$$Y = a + bx \quad 1.4$$

This process may be repeated until the fit is satisfactory. Therefore, to summarise,

- i) Plot the observed proportions (p) accepting as probits (Y) against gap size (x).
- ii) Fit, by eye, a line through these points and obtain new values for Y.
- iii) Compute $y = Y - (p - P)/Z$ for each value of x, together with weighting coefficients.
- iv) Fit a new line through the weighted points x, y.
- v) Repeat iii) and iv) as necessary.

(Tables of weighting coefficients, $Y - P/Z$ and probits have been constructed to make computation simpler - cf. ref. 2.28.)

Appendix II : Analysis of Lag Acceptance Data

Using the data from Table 2.3 and Table 1X, ref. 2.28, we have Table II.1. The probits are plotted on fig. II.1. The first line was fitted, not by eye, but by least squares to the unweighted points.

Let the line be of the form

$$y = a + bx$$

where y = probit,

x = nominal lag size(s).

$$\text{Then } b = \frac{\sum xy - \frac{\sum x \cdot \sum y}{n}}{\frac{\sum x^2 - (\sum x)^2}{n}}$$

$$= \frac{60.27 - (12.00 \times 14.63)/3}{50.00 - 12.00^2/3}$$

$$\therefore b = 0.875$$

$$\text{and } a = \bar{y} - b\bar{x}$$

$$a = 14.63/3 - 0.875 \times 12.00/3$$

$$= 1.3766$$

$$\therefore \text{First line is } y = 1.3766 + 0.8750x$$

From Table 1X.2, ref. 2.28, we have Table II.2, where

p = Proportion accepted,

x = Nominal lag size,

y = Probit predicted from first line,

$y-p/2$ = Minimum working probit

$1/Z$ = Range

w = Weighting coefficient
 n = No. of observations.

From Table II.2,

$$\begin{aligned}
 \sum wn &= 58.851 & \sum wnx^2 &= 1056.642 \\
 \sum wnx &= 239.666 & \sum wny^1 &= 291.349 \\
 & & \sum wnx y^1 &= 1268.303
 \end{aligned}$$

For second line, $y^1 = a^1 + b^1 x$

$$\sum wnx y^1 - b^1 \sum wnx^2 - a^1 \sum wnx = 0 \dots\dots\dots \text{II.1}$$

$$\sum wny^1 - b^1 \sum wnx - a^1 \sum wn = 0 \dots\dots\dots \text{II.2}$$

(The derivation of equations II.1 and II.2 is given in ref. 2.27).

Substituting in equations II.1 and II.2,

$$1268.303 - 1056.642b^1 - 239.666a^1 = 0$$

$$291.349 - 239.666b^1 - 58.851a^1 = 0$$

Solving simultaneously for a^1 and b^1 ,

$$b^1 = 1.0147, \quad a^1 = 0.8185$$

Second Line is $y^1 = 0.8185 + 1.0147x$

Use the Chi-Squared Test to test the fit of this line to the observed data in Table II.3, where

x = Nominal lag size
 y^1 = Probit predicted from second line
 $p(e)$ = Proportion acceptances (from y^1 and Table 1X, ref. 2.28)
 $n(e)$ = Number of acceptances expected
 $n(o)$ = Number of acceptances observed.

From Table II.3, $\chi^2 = 1.0525$, 4d.f. (90% sig).

\therefore The line $y^1 = 0.8185 + 1.0147x$ is accepted

From the accepted line,

$$\sigma = 1/b^1 = 0.9855s$$

$$\mu = (5 - a^1) = 4.1208s.$$

The cumulative normal curve with mean 4.1208s and standard deviation 0.9855s is shown superimposed upon the observed data in fig. 2.8.

Appendix III : Analysis of Gap Acceptance Data

Using the data from Table 2.4 and Table 1X, ref. 2.28, we have Table III.1.

The probits are plotted on fig. III.1. The first line was fitted, not by eye, but by least squares to the unweighted points.

Let the line be of the form

$$y = a + bx$$

where y = probit, x = nominal gap size (s).

$$\text{Then } b = \frac{\sum xy - \frac{\sum x \cdot \sum y}{n}}{\sum x^2 - \frac{(\sum x)^2}{n}}$$

$$\therefore b = 0.5908$$

$$\text{And } a = \bar{y} - b\bar{x} \\ = 1.8688$$

$$\text{First line is } y = 1.8688 + 0.5908x$$

Using Table 1X.2, ref. 2.28, Table III.2 is drawn up in the manner described in Appendix II. From Table III.2 the equation of the second line is obtained:

$$\text{Second Line is } y^1 = 1.1401 + 0.7516x$$

Table III.3 is constructed as described in Appendix II, and a Chi-Squared Test performed to test the fit of the second line to the observed data.

From Table III.3, $X^2 = 4.1865$, 8 d.f. (80% sig.).

\therefore The line $y^1 = 1.1401 + 0.7516x$ is accepted.

From the accepted line,

$$\sigma = 1/b^1 = 1.3333$$

$$\mu = 1.3333 (5 - 1.1401) = 5.1352.$$

The cumulative normal curve with mean 5.1352s and standard deviation 1.3333s is shown superimposed upon the observed data in fig. 2.9.

Appendix IV : Analysis of Gap Acceptance Data (All Gaps)

Using the data from Table 2.5 and Table 1X, ref. 2.28, we have Table IV.1. The probits are plotted on fig. IV.1, the first line, a fit by least squares to the unweighted points is given by

$$\text{First Line is } y = 1.716 + 0.545x$$

where y = probit and x = Nominal Gap Size(s).

From Table 1X.1, ref. 2.28, we have Table IV.2, constructed as in Appendix II. By fitting a second line to the weighted points in Table IV.2,

$$\text{Second Line is } y^1 = 1.0280 + 0.6568x$$

Table IV.3 tests the fit of this second line to the observed data by the Chi-Squared Test. The result of this test is inconclusive. Using the second line to fit a third line, together with Table 1X.2, ref. 2.28, Table IV.4 is constructed. The third line, fitted to the weighted points, gives

$$\text{Third Line is } y^{11} = 0.7191 + 0.7193x$$

Table IV.5 tests the fit of this third line to the observed data. The fit of this third line is little better because the plot of the probits is a curve (fig. IV.1) and in this case a plot against the logarithm of the gap size would probably yield a more satisfactory fit. Such a transformation would, however, make comparison with the curves shown on figs. 2.11 and 2.12 impossible, and so it was not attempted. From the second line, therefore,

$$\sigma = 1.5225s \quad \mu = 6.0473s.$$

The volume of the opposing flow over the period for which the gap acceptance behaviour was observed (Ashworth's 'major road volume,' q) was 0.2416 veh/s. Therefore the mean of the observed distribution should be shifted $s^2 q$, i.e. $1.5225^2 \times 0.2416 = 0.5823s$. to give the distribution of minimum acceptable gaps. The mean therefore becomes $6.0473 - 0.5823 = 5.5450s$.

Appendix V : Analysis of Gap Acceptance Data for Groups of Two Vehicles

Using the data from Table 2.8 and Table 1X, ref. 2.28, we have Table V.1. The probits are plotted in fig. V.1, and the first line was fitted by least squares to the unweighted points.

If the line be of the form

$$\begin{aligned} y &= a + bx, \\ b &= (210.10 - 39 \times 30.90/6)/(271 - 39^2/6) \\ &= 0.5285 \\ \therefore a &= 30.90/6 - 0.5285 (39/6) \\ &= 1.7148 \end{aligned}$$

\therefore First Line is $y = 1.7148 + 0.5285x$

From Table 1X.2, ref. 2.28, we have Table V.2 (see Appendix 11 for more complete description of the method), and the second line is obtained

$$\text{Second Line is } y^1 = 0.7859 + 0.6868x$$

Table V.3 is constructed as in Appendix II, and a Chi-Squared Test performed to test the fit of the second line to the observed data. From Table V.3, Chi-Squared = 1.768, 7d.f.

\therefore The line $y^1 = 0.7859 + 0.6868x$ is accepted

From the accepted line,

$$\sigma = 1/b^1 = 1.4560s$$

$$\mu = 1.4560 (5 - 0.7859) = 6.1357s.$$

For the normal distribution

The cumulative normal curve with mean 6.1357s and standard deviation 1.4560s is shown superimposed upon the observed data in fig. 2.18.

Appendix V1 : Example Calculation of Traffic Signal Settings

Details of a hypothetical four arm traffic signal controlled intersection are given in Table V1.1. The calculations shown below are on the lines recommended in ref. 2.3 and 2.6, and any symbols used below take the meaning defined in these two works, unless otherwise stated. The calculations are in two parts: the first calculates the optimum signal settings for the hypothetical intersection using the recommended RRL method throughout (using 1.75 as the right turning vehicle factor); the second is similar except that simulated right turning vehicle factors are used.

1. Right turning vehicle factor = 1.75

For the north approach:

$$\begin{aligned} S &= 3200/(1) (1 + 0.75 \times 0.03) \\ &= 3130 \text{ veh/h} \\ \therefore y &= 600/3130 = 0.192 \\ &\text{(Assuming that all the vehicles = 1 pcu)} \end{aligned}$$

For the south approach:

$$\begin{aligned} S &= 3200/(1) (1 + 0.75 \times 0.15) \\ &= 2876 \text{ veh/h} \\ \therefore y &= 900/2876 = 0.313 \end{aligned}$$

For the west approach:

$$\begin{aligned} S &= 1900/(1) (1 + 0.75 \times 0.05) \\ &= 1831 \text{ veh/h} \\ \therefore y &= 100/1831 = 0.055 \end{aligned}$$

For the east approach:

$$\begin{aligned} S &= 2250/(1) (1 + 0.75 \times 0.05) \\ &= 2168 \text{ veh/h} \\ \therefore y &= 120/2168 = 0.055 \end{aligned}$$

$$\text{Minimum cycle time } C_o = \frac{1.5L + 5}{1 - Y}$$

where $Y = y \text{ max.}$ Assume an all red time of 3s at each phase change and starting delays of 2s/phase. Then total lost time/cycle = 16s.

$$\begin{aligned} \therefore C_o &= \frac{1.5 \times 16 + 5}{1 - 0.313 - 0.055} \\ &= 29/0.632 = 46\text{s.} \end{aligned}$$

$$\begin{aligned} \text{Available effective green time} &= C_o - L \\ &= 30\text{s} \end{aligned}$$

$$\begin{aligned} \therefore g_{N-S} &= 30 \times 0.313/0.368 = 26\text{s} \\ g_{E-W} &= 30 \times 0.055/0.368 = 4\text{s} \end{aligned}$$

(In practice the setting of 4s is impossible to obtain on current signal controllers, and a higher value would be used. However, the theoretically optimum value will serve as a comparison in this exercise)

The calculations below check that the intersection will be able to cope with the right turning traffic with a cycle time of 46s.

For the south approach:

$$\begin{aligned} s_r &= 424 \text{ veh/h (fig. 22, ref. 2.3)} \\ n_r &= s_r \frac{(gs - qc)}{(s - q)} \\ &= \frac{424}{3600} \left(\frac{26 \times 3130 - 600 \times 46}{3130 - 600} \right) \\ &= 2.5 \text{ veh/cycle.} \end{aligned}$$

$$\begin{aligned} \text{Input hourly right turning volume} &= 15\% \times 900 \\ &= 135 \text{ veh/h.} \end{aligned}$$

$$\begin{aligned}\text{Average number of right turns/cycle} &= 135 \times 46/3600 \\ &= 1.725 \text{ veh/cycle.}\end{aligned}$$

Therefore the intersection can cope.

2. Using simulated right turning vehicle factors

For the north approach:

$$\text{Opposing flow} = 900 - 15\% = 765 \text{ veh/h.}$$

Use 5% right turns curve (fig. 2.25)

$$\text{Right turning vehicle factor} = 15$$

$$S = 3200/(1) (1 + 14 \times 0.03)$$

$$= 2253 \text{ veh/h}$$

$$y = 600/2253 = 0.266$$

For the south approach:

$$\text{Opposing flow} = 600 - 3\% = 582 \text{ veh/h}$$

Use 15% right turns curve (fig. 2.27)

$$\text{Right turning vehicle factor} = 7$$

$$S = 3200/(1) (1 + 6 \times 0.15)$$

$$= 1684 \text{ veh/h}$$

$$y = 900/1684 = 0.534$$

For the east approach:

$$\text{Opposing flow} = 100 - 5\% = 95 \text{ veh/h}$$

Use 5% right turns curve, fig. 2.25

$$\text{Right turning vehicle factor} = 1.5$$

$$S = 2250/(1) (1 + 0.5 \times 0.05)$$

$$= 2195 \text{ veh/h}$$

$$y = 120/2195 = 0.055$$

For the west approach:

$$\text{Opposing flow} = 120 - 5\% = 114 \text{ veh/h}$$

Use 5% right turns curve, fig. 2.25

$$\text{Right turning vehicle factor} = 1.6$$

$$S = 1900 / (1 + 0.6 \times 0.05)$$

$$= 1845 \text{ veh/h}$$

$$y = 100 / 1845 = 0.054$$

$$\begin{aligned} \text{Minimum cycle time } C_o &= 29 / (1 - 0.534 - 0.055) \\ &= 71s \end{aligned}$$

$$\text{Available } g = 71 - 16 = 55s$$

$$g_{N-S} = 55 \times 0.534 / 0.589 = 50s$$

$$g_{E-W} = 55 \times 0.055 / 0.589 = 5s$$

The results are compared in Table V1.2, which is repeated as Table 2.28.

Appendix V11 : Summary of Input Conditions for Traffic Signal Simulation Program

This appendix summarises the input data used in the traffic signal simulation program. Some of the input conditions have already been given in Chapter 2, and are not repeated here. The item numbers referred to below are the numbers given under the first 'comment' in the program printout in Section 2.4.4.

1. Run Number

This item refers to a set of input conditions. The purposes of each set of input conditions or run are given in Table V11.1.

2. Number and Time of Printouts

These varied, and no useful purpose would be served by detailing them here. A simulation time of 5h was used in the production runs, runs 17 - 113, for the reasons described in Section 2.5.3.

3. Scan Interval

This was held at a constant value of 1s.

4. First Random Number

See Table 2.14, Section 2.5.3.

5. - 11. Signal Timings

The signal timings for the production runs 17 - 113 are given in Section 2.6. Similar values were used in all the other runs apart from runs 2 - 8, and 913. The values used in runs 2 - 8 and 913 are given in Table 2.12.

12., 13. Approach Saturation Flows

These were constant at 1600 veh/h for all runs apart from run 913 (see Table 2.12).

14. Approach Volume

The approach volume used in runs 1, 9, 10 and 11 was 1000 veh/h. All other runs used 900 veh/h apart from runs 2 - 8, details of which are in Table 2.12.

15., 16. Turning Proportions

See Table V11.2.

17. Saturation Flow on Opposing Arm

3200 veh/h was used throughout, apart from run 913 when 2585 veh/h was used.

18. Opposing Volume

See Table V11.3.

19., 20. Vehicle Clearance Times

1.00 and 2.30s, respectively, were used for all runs.

21. Minimum Headway

1.00s was used for all runs.

22. RRL Right Turning Vehicle Factor

1.75 was used throughout.

23., 24. & 25. "Queue Jumping" Mechanisms

These facilities were used only in runs 2 - 8, when item 25 was set at 0.368.

Appendix V111 : Generation of Entry Speeds

It is necessary to generate an entry speed for the vehicles arriving at the entrance to the weaving section. Ref. 1.43, p. 105 states that

'The (speed distribution) curve is similar to that of a normal distribution with a standard deviation of 0.19 times the mean.'

This conclusion was based upon observations made at 50 points (admittedly in rural conditions), and so no attempt was made in this work to validate this result. It is therefore necessary to generate a distribution approximately to a normal distribution with a coefficient of variation of about 0.19 (coefficient of variation is the standard deviation divided by the mean).

Mention is made in Section 1.3.5 of the work of Francis and Lott (ref. 1.42) on the simulation of networks under area control. In their model, speeds were generated using a procedure which required as input the mean and the 'range' of the required distribution. (Their inaccurate usage of the work 'range' is discussed fully in section 1.3.5.) It was decided to test this procedure against the results obtained from the Road Research Laboratory.

A small program was written (not included in this text) which enabled any number of speeds to be generated with any input mean and 'range'. (The Algol text of the speed generation procedure may be seen under the identifier 'speed' in Section 3.5.4.) The results of the investigations may be seen in Table V111.1, and inspection of this table shows that when the input 'range' is equal to half the required mean, the coefficient of variation generated is approximately equal to the desired value of 0.19. Fig. V111.1 shows one of the speed generation exercises plotted as a histogram, with the normal curve superimposed. The two curves are statistically different at the 5% level, but inspection of fig. V111.1 shows that the fit is fairly close. Since the Road Research Laboratory data also approximates to a normal distribution, it may therefore be concluded that the speed generation procedure produces a speed distribution approximating to actually observed speed distributions, provided that the input 'range' is made equal to half the input mean.